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# CORAL BLEACHING

## HEARING

BEFORE THE

NATIONAL OCEAN POLICY STUDY

OF THE

## COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION UNITED STATES SENATE

ONE HUNDRED FIRST CONGRESS

SECOND SESSION

ON

CORAL BLEACHING

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OCTOBER 11, 1990

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# CORAL BLEACHING

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## THURSDAY, OCTOBER 11, 1990,

U.S. SENATE,
COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION,
NATIONAL OCEAN POLICY STUDY,
Washington, D.C.

The Committee met, pursuant to notice, at 9:40 a.m, in room SR-253, Russell Senate Office Building, Hon. Albert Gore, presiding.

Staff members assigned to this hearing: Grant Cunningham, professional staff member; John Moran, and Earl Comstock, minority staff counsels.

## OPENING STATEMENT BY SENATOR GORE

Senator GORE. I would ask the first panel of witnesses for the coral hearing to come up.

The hearing will come to order. I would like to welcome our witnesses and our guests. We are getting started just a few minutes late, because of the confirmation hearings that preceded this one, but I am really glad you are all here.

I am expecting this hearing to be a significant discussion of what may be the first biological signal of global warming. We will have three panels. We are going to hear, first of all, from experts on coral reefs.

This committee has been in discussion with the leading scientists in the sub-specialty of coral reef biology for most of this year. The discussions began prior to a rather extensive set of investigations and experiments that were planned before this year's anticipated bleaching event, and after they returned from the reefs we continued the discussions, and I wish to thank the scientists in helping the committee think through the best way to design this hearing and examine this problem.

The second panel, after the specialists on coral reefs, will be a panel on global temperature data. This is not in my printed opening statement, but let me just say that in talking with the witnesses on the temperature panel I found out that we will be presented some rather startling evidence in that second panel. The year 1990 is now shaping up as by far the hottest year in recorded history, not just by a little bit, but by a significant amount. The month of March in particular is completely off the charts, beyond any previous month that has ever been measured.

We will hear from some distinguished scientists in that panel, including Phil Jones from the University of East Anglia, who has traveled from England for this hearing. I am especially pleased he is here, because I went to visit with that group

in East Anglia a couple of years ago. I think they have the best temperature record constructed in the world.

They will be joined by the team from Huntsville, Alabama, whose work was widely misinterpreted earlier this year in rather simplistic headlines that said the most sophisticated measurement of temperatures now shows no global warming in the 1980's.

They are a little concerned their work was misinterpreted by people who did not read it carefully, and they are here to talk about their work, which is really extraordinary, and a tremendous scientific feat of measurement. They are going to tell us what it means, what it does not mean, and what similar and related measurements can tell us about global warming.

While the trend during the 1980's was erratic, and there were some hot years in the beginning of the decade, in fact, the decade as a whole was significantly warmer than the previous decades, and we will hear more about that.

In the third panel, we will hear from the agencies themselves, and what they think should be the Nation's response to the agenda which comes first from what we learn in the first panel about coral reefs. In talking with these scientists, I think we are going to find out that a lot more measurements, or many more measurements, need to be taken. Research needs to be more focused, and more attention needs to be paid to this first, clear biological signal of global warming.

We are going to ask the agencies about their response to the broader issue of global warming. Dr. John Knauss will be here at 11:45. He was going to be here earlier, but he has a meeting on whales today with the Japanese. Consequently his appearance will be delayed until 11:45. We are going to ask him about his agency's leading role in preparing for the response on coral reefs and global warming, including the second climate change conference coming up this fall.

Well, let me see. There is, in my opinion, a profound message for us by this occurrence in the coral reefs. As we will learn in greater detail from our first panel today, the news from the field is alarming. Having suffered repeated bouts of bleaching, coral reefs are beginning to show signs of exhaustion and die off.

To those of us who are nonscientists, bleaching—I am told—can be thought of as a kind of starvation. In the early 1980's, the reefs held on during times when they were without food, and were even able to rally back when their food supply was replenished. It seems, however, that their fight has gone on one round too many. Stressed and fatigued, the coral reefs are now dying. They no longer seem able to spring back from their injuries quite as readily after repeated events.

I believe there is a profound message for us in their experience. These animals live on the edge, so to speak, in the biosphere, acutely sensitive to many types of disturbances. The reefs act as a finely tuned radar system. The way coal miners used to carry canaries into the mines to find out when the conditions were dangerous, we can perhaps look at the coral reefs as an early warning signal of conditions in the biosphere to which we should react.

Today, with their deaths, they are reacting in the most extreme manner, and it is at our own peril that we turn a deaf ear to the alarm bells they are ringing. Coral reefs are some of the richest marine ecological systems in the world, and while they may best be appreciated for their decorative beauty, they play a key role in the marine ecosystems. They provide shelter to a vast array of marine life, and by breaking waves that pound the beach, they provide essential protection to people living in coastal communities in the United States and abroad.

They also play another important role. Corals take carbon dioxide out of the atmosphere. They fix carbon dioxide in the reefs themselves, and if they die, then the amount of $CO_2$ taken out of the biosphere each year naturally can be expected to fall off.

What is killing the corals? Well, our first panel of scientists has labored long and hard to try and solve this riddle. The first major worldwide bleaching event that attracted attention several years ago started an argument with some people saying, I wonder if this is caused by global warming, and other scientists saying, no, it cannot be that. There must be a lot of other explanations, and we need to look at all of the possibilities.

Well, the scientific community has been working for several years now to find out what is causing the death of—or the bleaching events and the resulting death of corals, and they have discovered an important clue. They found that the frequency and severity of bleaching events is exactly correlated with unusually warm ocean temperatures.

This discovery no doubt takes us much closer to understanding the coral bleaching phenomenon, but to identify the ocean, the hotter ocean water as the culprit, does raise the next question of why is the ocean getting hotter? That is where our second panel will come in.

I am particularly interested in hearing from this first panel. I, again, appreciate very much the amount of work that you have put into this effort, and to studying this phenomenon.

It is my hope that our second panel of experts will provide us with some provocative information in this regard. - I realize that our format today is somewhat unusual, and that it may not be immediately obvious as to why we have asked atmospheric climatologists to join us in a discussion of an event that is happening in the oceans. But, it is becoming increasingly clear that the oceans and the atmosphere are inextricably interconnected. We know for example, that the oceans absorb heat from the atmosphere and that the reefs in particular play a critically important role in offsetting the buildup of carbon dioxide gas in the atmosphere.

Similarly, we know that our emissions of carbon dioxide have been increasing at an exponential rate, and that the demise of the coral reefs has occurred at the same time that we have witnessed five of the hottest years on record. Is there a link here? Does the death of the corals indicate that- we are reaching a critical limit in the earth's natural ability to absorb greenhouse gases? We cannot, of course, answer these questions today. But in hearing the latest from the oceanographers and the climatologists, I believe that we can take an important step forward in identifying some of the pieces of the puzzle.

I have an opening statement that Senator Hollings would like to have included in the record.

[The statement follows:]

OPENING STATEMENT BY THE CHAIRMAN

This hearing will focus on coral bleaching. Back in 1987, through the Appropriations Committee, I chaired the Senate's first hearing on the bleaching of coral reefs in the Caribbean. In that hearing, we learned that very little is known about the causes of coral bleaching, which at that time had occurred on a massive scale worldwide. That was three years ago, and since then, there have been other bleaching events across the Caribbean and tropical Atlantic Ocean. Jamaican reefs, particularly, have experienced prolonged and extensive bleaching, and over the past few years, massive bleaching has occurred in the reefs of the Florida Keys.

This is not an insignificant or minor anomaly of nature. To the contrary, the severity of bleaching events has increased, causing deterioration of the reef structure and alterations in marine habitat. Further episodes of mass bleaching surely will lead to a major disruption of a vital marine ecosystem.

Today, we hope to explore new information on coral bleaching, gathered through the research conducted during the past three years. However, we cannot allow this information to become obscure—simply printed, placed on a shelf and forgotten. The information from this hearing should be a catalyst for focused research programs and funding. We must pursue the research necessary to provide us with important information about our environment. I believe we can never know too much about our environment, and coral bleaching exemplifies the fact we do not know enough.

I want to thank Senator Gore for chairing this hearing. I look forward to hearing the testimony presented as we continue to search for answers to the coral bleaching problem and its possible relationship to larger environmental questions.

Senator GORE. Our first panel is made up Thomas Goreau, senior scientist with the Discovery Bay Marine Laboratory at the University of the West Indies, in Jamaica; Raymond L. Hayes from the Department of Anatomy and the College of Medicine at Howard University here in Washington; Walter C. Jaap, Bureau of Marine Research at the Florida Department of Natural Resources in St. Petersburg; Robert Wicklund, director of the Caribbean Marine Research Center at Riviera Beach, Florida; and Ernest Williams, Caribbean Aquatic Animal Health Project with the Department of Marine Sciences at the University of Puerto Rico.

We welcome all of you here. Dr. Raymond Hayes will be our first presenter from the College of Medicine at Howard.

## STATEMENT OF RAYMOND L. HAYES, DEPARTMENT OF ANATOMY, COLLEGE OF MEDICINE, HOWARD UNIVERSITY

Mr. HAYES. Thank you, Mr. Chairman. I am Raymond Hayes, professor and chairman of the Department of Anatomy at Howard University College of Medicine. As a developmental biologist and a human anatomist, my interest in corals is derived from the efficiency with which these organisms engage in calcification.

Mr. Chairman, I consider it an honor to appear before this committee to introduce the scientific panel and to discuss mass bleachings of tropical reef corals. I want you to know that coral reef bleaching is occurring at this very moment in the tropics. We believe that coral bleaching may signal global environmental changes which are not only a threat to the survival of selected marine organisms, but which also may be exerting progressively greater stresses upon the integrity of the entire tropical reef ecosystem.

I would like to start with a set of slides indicating the appearance of a normal reef.

Senator GORE. We are going to cut these lights so people can see. Is there any way to turn that screen a little bit so that our guests can see? I can move over here and look at it. Is that going to be a time-consuming process?

Mr. HAYES. It might be difficult with respect to the projector.

[Slides shown.]

Mr. HAYES. It is most important at the outset to establish the fact that the stony coral which produces the structural frame of the tropical reef which you see in this field——

Senator GORE. If we could turn the screen sideways there so that the angle is a little wider, and then move the whole screen this way.

Mr. HAYES. As I was saying, it is most important to establish the fact that the stony coral which produces the structural frame of the tropical reef, which is made of crystalline limestone or calcium carbonate, is an animal. This sedentary animal exists as collections of millions of individuals assembled into colonies, some of which you see on this particular slide.

The coral colonies vary from long or stubby branched configurations to dome-shaped or plate-shaped configurations.

In the second slide, you can see several examples of that.

Senator GORE. Now, the skeleton there is covered by a little, thin——

Mr. HAYES. Yes. There is a thin veneer of tissue, living tissue, which is roughly several millimeters in thickness.

Senator GORE. But that thin veneer of living tissue has actually created the skeleton.

Mr. HAYES. Yes, the skeleton is deposited under the living tissue.

Senator GORE. That is, as they reproduce, they leave the limestone-type skeleton and it gradually grows.

Mr. HAYES. That is right.

Senator GORE. But the skin is a living part of the coral itself, and it builds its own skeleton ever larger as it grows, correct?

Mr. HAYES. Yes.

Senator GORE. Okay. Go ahead.

Mr. HAYES. Now, that living tissue, as I indicated before, is covering this mass of skeleton which is accumulating as the colony expands, and the tissue consists of a functional and structural unit which we refer to as a polyp, such that millions of these polyps are assembled into a colonial form. [Slide]

Mr. HAYES. What we are looking at here in these pictures are independent colonies of these many polyps that are assembled.

So, as shown in this diagram, in the upper left corner one sees the typical topography of a tropical reef, and within that reef one has independent colonies, and within each colony are millions of individual polyps. The structure of the polyp is such that the cells are organized into two layers, or sheets of tissue, which are held together by a thin glue, or connective tissue.

In this particular picture, one sees such a polyp magnified many times.

Senator GORE. So it is a very tiny animal that lives in groups, and it cannot survive by itself. It is a communal animal, but each individual polyp is a very little tiny critter.

Mr. HAYES. It is very small, on the order of several millimeters in diameter. These organisms will reproduce asexually, all the while laying down a calcareous skeleton underneath.

Senator GORE. What is "calcareous"?

Mr. HAYES. Calcium-containing.

Now the structure of the coral itself, as I indicated, was that of two sheets of cells or epithelial sheets, and the innermost of these epithelial sheets harbors a small unicellular plant which is referred to as a zooxanthellae. This is an algal cell which lives very comfortably in a symbiotic relationship with the coral tissue.

Senator GORE. Now is that what the British scientists call zooxs?

Mr. HAYES. That is what the British scientists call zooxs.

Senator GORE. Z-o-o-x?

Mr. HAYES. Z-o-o-x, yes.

Senator GORE. Now the zooxs are actually little algae; is that right?

Mr. HAYES. Yes.

As shown in this slide in the lower right, one has a very highly magnified zoox which contains chloroplasts and which is a photosynthetic organism.

So the algae photosynthesize in response to light, and the coral organism derives certain nutritive benefit from the products of the algae. For example, one of the products of photosynthesis is oxygen, which the animal tissue then uses for respiration.

The outer layer of cells of the polyp are responsible for creating currents to move water and suspended particles past the mouth of the coral. It is in this layer also that we find stinging cells which are used to capture planktonic food for the coral nutriment.

The basal segment of the outer layer is responsible for deposition of the skeleton. The process of skeletal formation occurs very slowly and irregularly, since it fluctuates according to the time of day as well as the season of the year.

The net growth rate of most corals is measured in millimeters per year, with the most rapidly growing coral depositing its skeleton at a rate of about 10 to 12 centimeters per year. In a coral colony of one of the major reef framebuilders, it would take over 100 years to reach a height of 1 meter or slightly greater than 3 feet.

I mentioned before that the inner layer of cells harbors the unicellular algae or the zooxs. This layer is also specialized for reproduction and for digestion of food which is brought into the stomach cavity of the cup-shaped polyp. These cells will synthesize digestive enzymes and mucus to be mixed with the food so as to extract nutriment for the benefit of the coral.

The zooxanthellae which are residing within this inner layer are, as I indicated before, algae. They are yellow-brown algae. These plant cells are harbored very securely within membrane-bound vesicles within the coral tissue, and they live there in symbiotic balance.

The production and the nutritive environment provided by the coral is of benefit to the algae, and the algae in turn produce metabolic wastes that are utilized by the coral.

The algae, in other words, represent the coral's vegetable garden, and the coral serves as the provider for the growth and multiplication of this cellular population. So both the animal and the plant tissues derive benefit from the relationship.

This is another picture of a normal reef.

In contrast his is a picture of a stressed colony. Under conditions of stress, the symbiotic relationship between the coral and the algal cell dissociates. The algal cell as the mobile component in this assemblage may be expelled by the coral or may choose to leave. The determinants of this intricate relationship unfortunately are poorly understood, but from laboratory experiments we do know that many factors will trigger that dissociation. For example, maintaining the corals in extended periods of darkness will cause the algae to depart. Drastic sudden changes in salinity, temperature or turbidity will also uncouple the relationship.

Once the algae are separated, the coral tissue loses its yellow-brown color and appears light tan or even white, as shown in the segment of the colony that you see here.

Here is another picture of a partially bleached colony. What we see around the edges of the colony in the lower portion of the field is the normal yellow-brown coloration, but on the top of the colony we see various stages of bleaching; that is, various stages of subtraction of algal pigmentation from the coral.

The animal tissue itself is both colorless and transparent, so the white color that you see after the loss of the algae is that of the skeleton of the coral. It is the calcium carbonate that is attributing the whiteness.

The similarity of this condition to what might be imagined were a strong bleach poured over the animal has led to the use of the term "bleaching" to describe the change in appearance of the corals, but it is important to emphasize that this response in the field is not the result of a chemical exposure but is explained entirely by the loss of algal pigmentation. So coral bleaching has been chosen by marine scientists as a shorthand to refer to that condition when the limestone skeleton of the coral is visible and, therefore, determines the color of the colony.

On a histological level using light microscopy, these are stained sections of a normal coral. The inner epithelial sheet housing the zooxanthellae is shown in the lower righthand side of the field. The outer epithelial sheet is shown in the

upper left portion, and the cementing glue between the epithelia is shown in the middle.

Now by contrast, when bleaching occurs the scene as shown in the next slide appears.

That is, that the inner epithelial sheet is disrupted, the majority of the algae have departed, and there is an accumulation of a mucoid residue in the vicinity that once was occupied by this population of zooxanthellae. Again, the upper or the outer epithelial sheet appears to be intact and, for all intents and purposes, is normal.

We know that the coral in the bleached condition is not necessarily dead. When bleached, however, its vitality is soon impaired. The bleached coral does not continue to produce a skeleton and may not even be able to sustain earlier deposits to which the colony is attached. So the net growth of the limestone reef is lost during episodes of bleaching.

In addition, the metabolism of the coral is reduced significantly. This is partly due to the loss of byproducts from the algae, but it is also due to the fact that the coral is famished. It is starving and, therefore, unable to gather food for itself from the water column. The ability of the coral to clean itself of sediments and to kill planktonic parasites are also compromised.

It is not surprising, therefore, that mortality of bleached corals is high. Only the fortunate colonies which repopulate with algae soon after bleaching are able to survive. Their ability to recover depends upon:

One, the removal of stress factors which initially induced the bleaching;

Two, time; and

Three, the availability of a viable stock of zooxs to repopulate the coral tissues.

Environmental factors which induce bleaching are beyond the control of the coral. Even under ideal circumstances the animal lives close to its tolerance limit for many of these variables. It requires only slight changes in temperature, salinity, or turbidity to induce a stress response such as bleaching. Time of exposure to stressful conditions again is beyond control by the coral. As time is prolonged and as stress level is sustained, the chances of recovery from bleaching are significantly reduced.

The zooxanthellae which are released from the coral by flushing with mucus probably do not survive, so the availability of algae for repopulation of the bleached coral is poor. The bleached coral is at risk of not recovering at all. The death of the coral is rapidly followed by overgrowth from other organisms which aggressively compete for space on the reef. These other organisms, however, are not likely to contribute to the growth of the reef frame.

With this background on the organization of the tropical coral reef and the structural features of coral tissues, the symbiotic relationship with the plant cells or zoox, and the stress response of bleaching, I would like to turn the program over to Dr. Walter Jaap, who will focus on bleaching as observed in the Florida reef environment.

Thank you.

Senator GORE. Thank you very much.

Let me just briefly summarize what I heard you say, the way I understand it.

Coral reefs are comprised of three elements: the skeleton, which is the result of years of growth; the thin skin of the living animals, coral polyps, that build this skeleton; and the specialized algae or zooxs that live inside the skin of the polyps.

The color of a coral reef comes from the algae in the skin of the animals, but these algae are sensitive to stress such as the stress of increased temperature, changes in salinity and other variables, and they are either expelled or choose to

leave the skin of the animals. When they do, that skin becomes transparent, and the white skeleton underneath shows through, and it looks as if it has been bleached.

After the algae are gone, the animals, the coral polyps, find it very hard to get along because they depend on the algae in a symbiotic relationship. They get energy from their photosynthesis, and they can get along for a while so long as the algae come back.

If the bleaching occurs every year or for a prolonged period of time, the coral polyps get exhausted and start to die. Then the reef dies.

That is sort of what I get from your testimony.

Now Mr. Jaap, you have been there looking at these bleaching events, and we welcome you. Please proceed.

**STATEMENT OF WALTER C. JAAP, FLORIDA MARINE RESEARCH INSTITUTE, FLORIDA DEPARTMENT OF NATURAL RESOURCES, ST. PETERSBURG, FL**

Mr. JAAP. Thank you, Senator. It is my privilege and honor to be here today. I thank you again for inviting us to make this presentation. I am going to try to discuss briefly the historical perspective of bleaching in Florida. I have some documentation, slides as well, and also some video that I hope I will have an opportunity to show you.

Senator GORE. All right, good. We need to compress these presentations.

Mr. JAAP. I understand that.

The Florida reef tract extends approximately 220 kilometers from Key Biscayne to Dry Tortugas, Florida.

[Slides shown]

Mr. JAAP. This is a chart showing the area of Miami southward to the Dry Tortugas, the extent of the Florida reef tract to which I referred. It includes 6,000 coral reefs located in depth from a few feet to more than 100 feet.

That system which is unique on the North American continent has experienced increasing, more frequent episodes of bleaching that has damaged the reefs and corals and perhaps threatens the future productivity and existence of these reefs.

The economic significance of this reef system cannot be underestimated. We recently had a ship grounding where we calculated that 5,000 square meters of reef area in the Florida Keys is worth approximately $13 million.

Coral reef bleaching events result from the loss, as Dr. Ray Hays has said, of endosymbiotic algae. Florida reefs have experienced massive bleaching episodes going back as far as we can look in the literature to around 1911, but since 1973 we have had three major events, and again now in 1990 we are experiencing another event.

This summer's episode was first reported from Looe Key National Marine Sanctuary, with the first evidence seen somewhere near July 25. Billy Causey, manager, Love Key National Marine Sanctuary documented a great deal of this particular event because it happened at that site first.

Go back to that slide, please.

Senator GORE. Now you say it has gone back to 1911.

Mr. JAAP. Yes.

Senator GORE. Has it become more frequent in recent years?

Mr. JAAP. Yes, it has, Senator.

Senator GORE. It is more pronounced and extensive?

Mr. JAAP. Yes, sir.

Senator GORE. All right, go ahead.

Mr. JAAP. By August 13, Looe Key Reef had severely bleached due to elevated seawater temperature. In contrast to some of the other bleaching events, during the same decade, reefs off the Key West and Key Largo area did not experience bleaching at the same time as Looe Key. Colleagues have informed me, however, as of last weekend that they are beginning to see the precursors to some of this bleaching.

Doldrum weather conditions, water temperatures in excess of 30 degrees Celsius, virtually no wind or waves, poor circulation, strong ebb tides that transported in-shore turbid water masses to the reef tract are suggested as the causative factors for this particular event.

Very hot water, at 33 degrees Celsius which is about 91 degrees East with elevated salinity of 40 parts per 1,000 was reported at Long Key, which is just a little bit above Looe Key area, by David Forcucci, an employee of the Florida Keys Regional Marine Laboratory. This water was flowing out of Florida Bay during tide cycles and sinking to the bottom, impactir g coral reefs.

If I could see the next slide, please.

This is the typical color of the fire coral. The previous slide you saw was actually one that was terribly bleached out. This is what this species looks like under normal conditions. The zooxanthellae give it that color, as previously discussed.

All right, this is again another photograph through a microscope. Looking at the little round orange spherical objects in there, those are the zooxs providing the energy for the animal.

If we go to the electron microscope, this is what a healthy zoox looks like. The small structures around the periphery are the chloroplasts, the functional areas where the energy is transferred from sunlight into carbon compounds such as sugars, oils and fats.

The precursor of the bleaching events, as Ray has shown you in other slides, is basically a coral that has a mottled appearance. It has some areas that are naturally colored or lighter, and then the bleaching progresses until the entire colony turns white.

This is again another colony showing precursor conditions.

This is one that has gone through the entire process. All the zooxs are virtually gone. It will take probably 4 to 6 weeks if the conditions return to normal for that to recover. In many cases, we are seeing that they are not recovering. I think the frequency of the episodes has drained a lot of energy out of the system, and they are not able to recover as rapidly as they used to.

This is another organism that is important in the reef ecosystem. We call it the golden sea mat. It is more sensitive, I would say, than the stony corals or the fire corals. It generally tends to bleach earlier, and at Looe Key now 60 percent of the population of this species has been extirpated or killed by the bleaching event.

This is an area off of Key West which frequently undergoes bleaching. Back in 1987 this particular reef system was extremely bleached out. We are conducting studies there now, and some of the coral populations have been significantly decreased since that time.

Even from the air, one can see the bleached corals on the top of the surface of the reef. The white splotches you see by the lighthouse are all areas of bleached coral.

Again, this sort of condition that you will see the water starts to get warm.

Again, a totally bleached golden sea mat.

This is some water temperature data in the 1983 event during another bleaching. It documents how hot the seawater gets. We see temperatures getting up to 34 or 35 degrees C, and it is not the average temperature with which we

are concerned here. It is the extreme temperature that really stresses the organisms.

Senator GORE. What is that in Fahrenheit?

Mr. JAAP. Thirty is approximately 85 degrees, I believe, Senator.

Senator GORE. You said it was up to 34 or 35?

Mr. JAAP. Yes, sir.

Senator GORE. What is that?

Mr. JAAP. That would be 93 to 95 degrees F.

Senator GORE. All right.

Mr. JAAP. We are looking at temperatures where 3 to 5 days are sufficient to cause bleaching episodes.

The tides also influence treating of the water column. If low tides occur at or near midday, water level on the top of the reef is significantly reduced, and the water temperature increases, and it brings the stress down onto the corals.

This is an example of a doldrum period. It is usually what precipitates the event. The wind drops off for 3 to 5 days. We get extreme sunlight penetration in the water column, very few clouds. The water is like a mill pond, it normally would have 3-foot seas under a normal tradewind condition. Then the heat starts increasing the temperature of the water column.

This is the model that we propose for this. Massive evaporation causes density sinking, which is essentially a lot of the salt remaining in the water column while the water evaporates. The surface water becomes heavy, sinks in hot layers, and impacts the corals, inducing the stress.

Under normal circumstances this water would be mixed quite a bit by currents and wave action, but under a doldrum-like condition these masses of water, hot water remain intact, sink, and produce stress. We felt them in the water. We have not yet really had a chance to study them, but you can actually feel them with your body if you are swimming through it.

This is what happens as a result of treat stress. These corals are all bleached out. You can see a great number of them.

In closeup, one of the things that you would say is that this is dead, but if you put you wrist up against that fire coral you would want to go for first aid. It still has the potential of stinging you, and it will remain viable for a period of probably 2 to 3 weeks. If the zooxanthellae do not come back in there, however, this animal has no other source of food. It requires photosynthesis to replenish the energy. So it will die after maybe a 3- to 4-week period.

We can test these things to see if they are alive with a very simple test, as I mentioned.

To give you an idea of the latitude of distribution, in 1987 we had bleaching as far north as Palm Beach, Florida, which was very unusual. These events were restricted in the early times (in the 1970's) to around the area of Key West and the middle part of the Keys. Now it is extending further and further up, and these corals are less adapted to the warmer temperatures than the ones down in the Keys.

Senator GORE. 1987 was the first time the scientific community really started looking at this?

Mr. JAAP. It got our attention, yes, because that episode was much significantly greater. My colleagues will talk more on the distribution of bleaching episodes.

Senator GORE. This has happened all over the world?

Mr. JAAP. They will discuss that, yes.

Senator GORE. All right. Go ahead.

Mr. JAAP. One of the things that happens is these corals are weakened, and they are infected with fungi. This is an electron photomicrograph of one of the fungal filaments that got into the coral tissue and caused the decomposition. We are not sure whether this is actually an infection or just simply a situation where these fungiare decomposing dead coral tissue; but it is an enigma.

The previous slide was an electron micrograph, and this is light microscopy. The little black wiggly worm-looking things are all fungal hyphae that are intermixed with the coral tissue.

Growth is affected by these bleaching events. We actually see total succession in some cases of growth of these corals. Also, reproduction is terminated. We do not see sexual reproduction going on after a bleaching event. So a bleaching event can impact the coral reef community in a drastic way, and we are getting concerned that this is going on more frequently.

As I said, if the corals are not given respite from this stress, we see the death of the corals. This is the first sign that these corals have succumbed. This fine film of algae starts to grow on that skeleton that was previously bone white, indicating that the animal has given up and died.

Those are all my slides. I think in consideration of time I will not show the video, and I will defer to your questions.

Senator GORE. What was the video, and how long was it?

Mr. JAAP. Well, we have approximately 5 minutes of video that I could show. If you would prefer to see that, I can do that.

Senator GORE. I think we had better save it and move along. If we have time at the end of the panel, we will show it then.

[The statement follows:]

STATEMENT OF WALTER C. JAAP, FLORIDA MARINE RESEARCH INSTITUTE

Coral reefs are complex marine ecosystems that provide food, shelter, and breeding sites for a multitude of marine organisms. The reefs benefit man by serving as carbon dioxide buffers, by providing storm protection, by supporting fisheries, and by providing opportunities for recreation. Florida's reef tract extends 220 miles from Key Biscayne to Dry Tortugas and includes 6000 coral reefs located in depths from a few feet to more than one hundred feet. That system, unique on the North American continent, has experienced increasingly more frequent episodes of bleaching that damage the corals and threaten the future productivity of the reefs.

Coral reef bleaching events result from the of loss of endosymbiotic algae (zooxanthellae) contained within the tissues of corals and other symbiont-bearing animals. In a bleaching event, the typical coloration disappears from the living tissue and the stark white color of the skeleton or underlying organic matrix is visible.

Water temperatures 2 to 3C above normal summer maxima and that last for two or three days are sufficient to cause a zooxanthellae expulsion (coral bleaching). Scientists also believe that increased ultraviolet radiation due to thinning of the earth's protective ozone layer may aggravate bleaching.

Florida coral reefs experienced massive bleaching episodes in 1911, 1914, 1958, 1966, 1973, 1983, 1987, and again in 1990. This summer's episode was first reported from Looe Key National Marine Sanctuary, with first evidence seen on July 25, 1990. Billy Causey (Looe Key National Marine Sanctuary Manager) documented the event with numerous observations. By August 13, the Looe Key Reef had severely bleached due to elevated water temperatures. In contrast to other bleaching events during the decade, reefs off Key West and Key Largo did not exhibit bleaching during this period.

Doldrum weather conditions (water temperature in excess of 30 C, virtually no wind or waves, poor circulation, and strong ebb tides that transport inshore, turbid water masses to the reef tract) are the causative factors of bleaching. Very hot water (33 C) with elevated salinity (40 ppt) was reported at Long Key by David Forcucci (Florida Keys Regional Marine Laboratory). This water was flowing out of Florida Bay during tidal cycles and sinking to the bottom at the nearshore patch reefs where it bleached the symbiont-bearing organisms. This year, bleaching appears to have been caused by two mechanisms: 1. localized heating around reefs due to doldrum weather conditions, and 2. hot and highly saline water transported from Florida Bay into the Atlantic.

Severe bleaching can reduce coral growth, suspend sexual reproduction, and in some cases kill the bleached organisms. Stress brought about by elevated water temperature results in loss of the principal source of energy. The symbiont-bearing animals obtain most of their energy from

photosynthetic sources, the zooxanthellae. Loss of this energy affects oxygen/CO2 balance, pH, and secondary productivity on the reef.

Historical water temperature data from 1878 to 1907 document that temperatures in the range of 31 to 32 C are not unusual during the summer. Seawater temperatures at Dry Tortugas were above 30C during 1989 and were near 30C at Biscayne National Park during 1978. These temperatures approach the upper tolerance limits for most reef corals and related symbiont-bearing reef animals. Even a small additional elevation of temperature will place the corals at risk.

Coral reefs influence global climate through their ability to bind CO2 to calcium in the building of limestone skeletons. This process is light- enhanced or expedited by the zooxanthellae. A moderate-sized brain coral produces nearly 12 kilograms (26.4 lbs) of limestone annually. An actively growing coral reef with a spatial area of 5000 m2 fixes 2.4 to 9.7 tons of C02 annually.Corals also fix CO2 through photosynthesis into sugar, starch, oil, and fat. Loss of coral reefs from the ocean will cause fundamental changes in the global CO cycle. The "greenhouse" effect may be enhanced if reefs are killed and the percentage of CO2 in the atmosphere is increased.

Bleaching episodes, deteriorating environmental quality, turbidity, and nutrient enrichment are presently threatening coral reefs on a global scale. If sea level rise accelerates and water temperatures increase, corals may be unable to grow upward to keep pace with the rising sea and reefs may be extirpated throughout the tropics.

We are aware that ENSO (El Niño Southern Oscillation) episodes are casually related to Florida coral reef bleaching events. Dr. Peter Glynn reported that every Florida coral reef bleaching episode was proceeded by an ENSO event. If global climate does experience a rapid change to warmer temperature, coral bleaching may be expected to increase. Corals may prove to be global canaries, warning us about the damage that man is inducing to the environments of Planet Earth.

## STATEMENT OF ROBERT I. WICKLUND, DIRECTOR, CARIBBEAN MARINE RESEARCH CENTER, RIVIERA BEACH, FL

Mr. WICKLUND. Thank you, Senator. I appreciate being here today.

We are part of the National Undersea Research Program, which is a division of NOAA. We are located in Florida and at Lee Stocking Island in the Exuma Cays, Bahamas, from where most of my observations have been made.

Mr. Chairman, it is an honor to appear before your committee to discuss what now appears to be a chronic problem with our coral reefs. Recurring bleaching and instances of damage are appearing in corals and other invertebrates throughout the seas of the Caribbean, Bahamas and Florida.

I was concerned with the extent of the bleaching event in 1987, but today I am dismayed. Our coral reefs are in peril and are disappearing at an alarming rate. My personal observations are from the seas surrounding mostly uninhabited islands in the Central Bahamas. The seas surrounding these islands are for the most part pristine and virtually untouched by pollution; yet even here the reefs are in trouble.

In 1987 we observed at least 15 species that were bleached, extending from the shallow waters of the Great Bahama Banks to the deep slope of Exuma Sound, beyond 200 feet deep.

Although an estimated 80 percent of the affected corals eventually recovered, mortalities following the bleaching were prevalent. Efforts to assign a cause to the coral bleaching phenomenon in 1987 and to discern the possible role of temperature in this and other biological processes were impeded by the fact that there were virtually no long-term data sets of temperature available for the Caribbean and adjacent regions, although sparse data indicated that warmer than usual temperatures were the problem in 1987.

Realizing that temperature anomalies may have played a role in this bleaching event, we responded early in 1988 by initiating a long-term Caribbean wide temperature study. Twenty-five to 30 subsurface recording thermographs were placed throughout the Bahamas, South Florida and in the Caribbean. The aim of this research was to evaluate the possible effects of temperature changes on coral reef ecosystems and trends that may be indicators of global temperature changes.

It is important that these recorders were placed in depths for the affected species. Tom Goreau is going to talk about satellite data later on, but we need to look at both the surface and the subsurface temperature data. There are processes and complexities of the temperature regimes that need to be looked at.

During the 2 years following the 1987 event, little bleaching was observed in the Bahamas, although some coral showed stress in 1989, particularly brain corals. In mid-August 1990, we observed early bleaching with a few small coral colonies. By mid-September bleaching was extensive, especially in the deeper reefs affecting about 25 percent of the live corals. The deepest observed bleaching just a few days ago was 150 feet on the Western slope of the Exuma Sound, with the shallowest in 4 feet of water.

By early October, the amount of bleaching was approaching the levels of 1987. We have not been able to get out in the last couple of days because of the storms in the Bahamas, but we believe the bleaching now has exceeded the 1987 levels. We found significant differences in temperature at two selected sites, at 6 feet and 60 feet, both where we found bleaching and recorders had been placed.

1990 highs were roughly 1.5 degrees Centigrade above 1988 and 1 degree higher than 1989 for the months of August and September. It does not sound like a lot, but these are significant considering that temperatures were up around 30 and 31 degrees.

There does not appear to be any major differences in the months prior to August. An additional reading of 30.1, which is about 86 degrees, was recorded at 100 feet deep. This is over 1 degree higher than anything else we ever recorded at that depth.

Mr. Chairman, the bleaching of corals and other species occurs almost simultaneously throughout the Caribbean and Florida. This is not a disease beginning at one location and spreading. It is something else that is happening. Some scientists believe that increased ultraviolet light may be implicated. We have been studying the effects of UVB on pure DNA in the ocean in cooperation with the Oak Ridge National Laboratory in Tennessee.

The primary effect of UVB in biological systems is DNA damage. We have quantified that UV-induced photo products damage. Our project is primarily to develop a system to monitor changes in UV that reach the ocean as a possible result of stratospheric ozone depletion and the effects these changes may have on marine organisms. Our results show that 13 percent damage occurs at 3 meters deep, quite a bit more than we found from the laboratory. So we cannot rule out that a potential threat to corals is UVB; however, I might add that finding damage down as deep as 150 feet and 200 feet does not indicate that UV-B is the cause

Senator GORE. That would tend to point more toward temperature?

Mr. WICKLUND. That's right.

Pollution is not the entire answer, either. Many parts of the Caribbean, including our own study sites, are relatively pollution-free but are negatively affected. O2 depletion is another possibility, but early data suggests not.

Although we cannot say with certainty that warm temperature is the cause of coral stressing and bleaching, the evidence definitely points to its playing a major role. We also cannot yet say that temperature patterns and coral bleaching events we see are indicative of global warming trends, but it is a legitimate hypothesis and should be tested by scientific research.

Whatever the causes may be, the evidence is clear that these immensely important ecosystems, our coral reefs, are in trouble. Although temperature and UV monitoring in the Caribbean have been initiated, these are only beginnings. Much more extensive monitoring is necessary if these and other parameters to establish the long-term physiological limits of fragile marine organisms are to be

known. We can no longer afford to respond after the fact. This is what we have been doing in the past.

Mr. Chairman, I can say that in no time during my 30 years involvement with the oceans, in which I worked quite a bit in the polluted New York Bight area—have I been as dismayed as I have been at the recent declining conditions of the subtropical and tropical reefs. These marine organisms live on a thin line of environmental constraints, a line which is now being frequently crossed.

It is already obvious that this committee is concerned. We hope that an urgency to understand what is happening to our reefs will prevail and that Congress and the administration will now take the decline of our coral reefs seriously and act quickly.

Thank you.

[The statement follows:]

STATEMENT OF ROBERT I. WICKLUND, DIRECTOR CARIBBEAN MARINE RESEARCH CENTER, NATIONAL UNDERSEA RESEARCH PROGRAM, NOAA

Mr. Chairman: It is an honor to appear before the U.S. Senate Committee on Commerce, Science and Transportation and the Nation-al Ocean Policy Study to discuss what now appears to be a chronic problem with our coral reefs. Recurring bleaching and incidences of damage are appearing in corals and other invertebrates, including sponges and sea anemones, throughout the seas of the Caribbean, Bahamas and Florida.

This is the second such hearing by the U.S. Senate. On November 27, 1987, I also testified before the Committee on Appropriations immediately following a bleaching event in the summer and fall of that year.

Mr. Chairman, in 1987 I was concerned, today I am dismayed; our coral reefs are in peril and are disappearing at an alarming rate. The observations and data that I have collected are from an archipelago of mostly uninhabited islands and cays with a total human population of only 500 along an 80-mile area. The seas surrounding these islands are, for the most part, pristine and virtually untouched by pollution, yet even here the reefs are in trouble.

Today, my testimony will describe work that has been conducted by the Caribbean Marine Research Center (CMRC) located at Lee Stocking Island, Exuma Cays, Bahamas. CMRC is a designated Center of the National Undersea Research Program, a division of the National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

During the late summer and fall of 1987 unprecedented levels of zooxanthellae loss resulted in bleaching and some mortalities in stony corals and other reef cnidaria and sponges throughout the Caribbean, Bahamas and southern Florida waters. Zooxanthellae, an endosymbiotic algae, is lost when the coral host organism is stressed and the algae is expelled.

CMRC scientists first observed extensive coral bleaching in the vicinity of Lee Stocking Island on October1, 1987. The observed affected organisms included several species of sponges, gorgonians and a sea anemone. At least fifteen species were affected, extending from the shallow waters of the Great Bahama Bank to the deep slope of Exuma Sound. The bleaching continued and worsened over several months. Although an estimated 80% of the affected corals eventually recovered, many were still bleached into January 1988. Mortalities following the bleaching were prevalent, especially in the Staghorn corals 30 to 60 feet deep. Staghorn coral on shallower reefs did not show as much damage.

Efforts to assign a cause to the coral bleaching phenomenon in 1987 and to discern the possible role of temperature in this and other biological processes were impeded by the fact that there were virtually no longterm data sets on temperature available for the Caribbean and adjacent regions. Sparse data indicated that warmer- than-usual seawater temperatures were involved, although these data were collected mainly from our seawater pumps that supply aquaculture research tanks and as such are not the best indicators of absolute temperature. However, when we compared these temperatures with those similarly recorded in 1986, significantly higher readings were evident. Median temperature for August/September was 31. 5C in 1986 and 32.5C in 1987.

Realizing that temperature anomalies may have played a role in this bleaching event, we responded early in 1988 by initiating a longterm Caribbean-wide temperature study. Twenty-five subsurface recording thermographs were placed at a 20-m depth in locations around the Bahamas, south Florida and the Caribbean, including Puerto Rico, St. John (V.I.), Barbados, Martinique, Belize, Honduras, Jamaica and Columbia. Other recorders were placed in depths ranging from two to 150 meters and at locations already being monitored as a follow up of the 1987 event.

The thermographs are calibrated against a mercury thermometer traceable to the U.S. Bureau of Standards and are programmed to record from every 10 minutes to every two hours, depending on their relativity to tidal influence.

This temperature project is conducted on a shoestring budget using any means possible to get the recorders placed around the Caribbean. Our results thus far have been promising even though several units have been stolen or lost. Two survived Hurricane Gilbert, one Hurricane Hugo, and several have not as yet been recovered. A wealth of information has been recorded and retrieved, however, and is awaiting analysis.

The aim of this research is to evaluate the possible effects of temperature changes on coral reef ecosystems, including important resource species, and trends in the Caribbean that may be indicators of global temperature changes.

It is important that these recorders were placed at the depths of the affected species to completely understand temperature within the water column. Although satellite data are useful, they only indicate the immediate surface temperature and do not take into account the complexities of temperature regimes below the surface.

During the two years following the 1987 event, little bleaching was observed in the Bahamas, although some corals showed stress in 1989, particularly Brain corals in deeper (30-60 ft) water.

In mid-August 1990, we observed early bleaching of a few small coral colonies. By mid-September bleaching was extensive, especially on the deeper reefs, affecting about 25% of live corals. The deepest observed bleaching was at 150 feet on the western slope of Exuma Sound with the shallowest up to four feet on the Bank. By early October the amount of bleaching was approaching the levels of 1987. Several corals and sponges that were observed bleached in 1987, but subsequently recovered, are now dying. The few surviving colonies of Staghorn coral on the offshore reef are now bleached and will probably die. Some preliminary work by the University of Maryland through CMRC indicates that, once affected, corals may be more susceptible to further stresses and could bleach more readily in the future.

CMRC scientists recently pulled some of the thermographs that were placed on or near previously known coral bleaching sites in the Bahamas. The data, although not yet treated, clearly show considerably higher temperatures in the late summer of 1990 than in 1988 or 1989

Significant differences in temperature occurred during August and September at both six feet and 60 feet. 1990 highs were roughly 1.5C above 1988 and 1.0C higher than 1989. There do not appear to be any major differences in months prior to August. An additional reading of 30. 1C at a 100-ft depth on September 27, 1990, was 1. 1C higher than any reading previously recorded at that depth over a three-year period.

Physical mechanisms exist in the Exumas and other places such as the Florida Keys that enable warm water from the shallows to reach areas offshore, potentially affecting the deepwater species. We have observed that heating and evaporation of seawater on the Great Bahama Bank during the summer will produce warm, high-density water with salinities up to 40 ppt (36 ppt is considered full oceanic seawater) that flows and sinks beneath cooler, less dense water and cascades down the slope. Thus, deepwater corals that are not acclimated to warm water can be affected by this unusual density flow. We have observed these density currents moving down the Exuma Sound slope to about 230 feet.

DISCUSSION

Mr. Chairman, the bleaching of corals and other species occurs almost simultaneously throughout the Caribbean and Florida. This is not a disease beginning at one location and spreading. Some scientists believe that increased ultraviolet light may be implicated. This is unlikely the problem in deepwater, considering the depths at which damage has occurred (220 ft). CMRC/NURP scientists have, however, been studying the effects of UV(B) on pure unprotected DNA in the ocean in cooperation with the Oak Ridge National Laboratory. The primary effect of UV(B) in biological systems is DNA damage. We have quantified UV(B)induced photo products (damage) in clear tropical waters, primarily to develop a system to monitor changes in UV(B) reaching the ocean and the effects these changes may have on marine organisms. We have found that DNA is the most basic and most accurate measurement of UV(B), more accurate in fact than very expensive photometers. Our results show that 13% damage (of the total damaging effects of UV(B) to DNA on the surface) occurs at 3 meters depth. This is much deeper than previous laboratory experiments have shown, so increased UV(B) cannot be ruled out as a potential threat to corals as deep as three meters where many are found.

Pollution is not the entire answer either. Many parts of the Caribbean, including our own study sites, are relatively pollution- free, but are negatively affected.

Laboratory studies recently conducted in Australia have shown that salinity changes do not induce bleaching of at least two species of coral, but corals held at 27C and subjected to 30 and 32C resulted in zooxanthellae expulsion rates 1000 times those of the control colonies.

Our field studies have twice now demonstrated that temperatures on reefs have been the highest during the two major periods of bleaching in 1987 and 1990. Our data also shows that temperatures during the months preceding August and September this year show no real evidence of an increase over the two previous years.

Although we cannot say with certainty that warm temperature is the cause of coral stressing and bleaching, the evidence definitely points to its playing a major role. We also cannot say that the temperature patterns and coral bleaching events we see are indicative of global warming trends, but

it is a legitimate hypothesis that should be tested through scientific research. Whatever the causes may be, the evidence is clear that these immensely important ecosystems, our coral reefs, are in trouble.

CMRC/NURP has initiated two major projects to address the bleaching problem. The temperature monitoring program has had a good start and our work with UV(B) is designed to establish a monitoring program using a very sensitive biological endpoint to measure the possible depletion of the stratospheric ozone layer, the main attenuator of UV(B). These are only beginnings, but the U.S. Government must support much more extensive monitoring of these and other parameters to establish the longterm physiological limits of fragile marine organisms. We can no longer afford to respond after the fact.

Mr. Chairman, I have spent my entire life in and around the sea and in the past thirty years have studied the oceans from the Arctic to the Tropics, much of my work concentrated in the polluted waters of the New York Bight. I can say that in no time during my involvement with the oceans, polluted or unpolluted, have I been as dismayed as I have been at the recent declining conditions of the subtropical and tropical reefs. These marine organisms live on a thin line of environmental constraints, a line which is now being frequently crossed.

It is already obvious that this Committee is concerned. We hope that an urgency to understand what is happening to our reefs will prevail and that Congress and the Administration will now take the decline of our coral reefs seriously and act quickly.

Senator GORE. Thank you very much

Ernest Williams with the Caribbean Aquatic Animal Health Project at the University of Puerto Rico is our next witness.

## STATEMENT OF DR. ERNEST (BERT) WILLIAMS, CARIBBEAN AQUATIC ANIMAL HEALTH PROJECT, DEPARTMENT OF MARINE SCIENCES, UNIVERSITY OF PUERTO RICO, LAJAS, PR

Dr. WILLIAMS. Thank you for inviting me to testify before the subcommittee today. My name is Burt Williams, and I am head of the Caribbean Aquatic Animal Health Project and professor in the Department of Marine Sciences in the University of Puerto Rico.

Our project has been attempting to follow and understand coral reef bleaching since 1987.

Could I have the first slide, please?

[Slides shown]

Dr. WILLIAMS. For your convenience, we have arranged for a new major worldwide coral reef bleaching event to be occurring for this hearing.

I am sorry. I could not resist a joke.

Although we predicted this major bleaching event which is now occurring in an article in Nature Magazine, we are not pleased that this destructive disturbance has actually begun. The first proof of global warming may well come from the bleaching of the fragile and highly sensitive coral reef system. Unfortunately, we do not have sufficient data to fully evaluate this intriguing suggestion because this gigantic series of disturbances has been understudied and virtually ignored.

Unraveling the mysteries of bleaching and many other possibly related major marine ecological disturbances is a vital component of any understanding of global processes and global changes. These disturbances may actually be alarms from the drastically changing and deteriorating marine environment.

Studying large scale disturbances will be expensive, but we can no longer afford to ignore the consequences and implications of these problems. Our own feeble attempts in following coral reef bleaching have disclosed a mechanism for predicting major bleaching events 1 year in advance. This can serve as a sufficient interval to organize and establish sophisticated research efforts to study this enormous problem.

We have also established a tentative cause for coral reef bleaching which invites experimental proof. All that is necessary is the support for these large

scale experiments. We have laid the groundwork for these experiments with practically our bare hands alone.

What is needed is the support and will to tackle these problems, not because we are humbled by the possibility of the massive destructive potential of major marine ecological disturbances, but because we are fascinated with the enormous potential of valuable knowledge available in understanding these fundamental processes.

Major marine ecological disturbances are modern-day sea monsters. They are far more dangerous and devastating than any of those from folklore, but they are filled with incredible amounts of vital information on the fate of our planet for those bold enough and with sufficient vision to face them.

Senator GORE. Could I ask you a question, Mr. Williams. You are speaking very carefully as a scientist. You know how much detailed scientific work has to go into proving and examining each of these hypotheses. You have spent a career in this field. Is it your personal opinion that the unprecedented bleaching phenomenon are related to global warming?

Dr. WILLIAMS. As we indicate in our paper which is appended in the written record of this hearing, it is our suggestion that this is directly related to the elevated sea water temperatures. These are only correlative information, but it is based upon reports—from hundreds of reports from all over the world, from various scientists.

There has been additional evidence from regional and smaller scale, recent studies. There have been some recent smaller scale studies that have also indicated that elevated temperatures are the cause, and even some of the recent analysis of large-scale temperature gathering are beginning to support the possibility of the elevated temperatures being the cause of coral bleaching.

Senator GORE. Is it your personal opinion that elevated temperatures will turn out to be the cause of these bleaching events?

Dr. WILLIAMS. Yes. I believe this is the major cause. The general deterioration of the marine environment and other local causes probably make the damage more great in local areas, but I think overall the cause will be found to be increased or elevated sea water temperatures.

Senator GORE. Okay, go ahead.

Dr. WILLIAMS. We will go to the charts instead of projections.

Senator GORE. I am sorry. Turn the lights on. You all have this better worked out than I did, and speak loudly.

Dr. WILLIAMS. Since the early 1980's, we have recognized a series of coral reef bleaching events, and these events can be grouped into complexes. The first complex began in 1979 and 1980, the second complex in 1982 and 1983, the third complex in 1986 and 1988, and the last complex is occurring right now. It began in 1989, and is continuing on in 1990.

In 1979, the event only occurred in the one area, and there were five areas in the 1980 event, and it was reported from the five areas in the Caribbean and the Pacific indicated by these arrows. There were probably many more areas in which this disturbance occurred but was not reported. These only represent where there were published records of bleaching for those years.

In 1982, a major bleaching event occurred on the Great Barrier Reef of Australia. The following year, 1983, the bleaching—particularly intense bleaching in the Eastern Pacific destroyed entire coral reefs, and large numbers of corals died in the Eastern Pacific. There was moderate bleaching in the Caribbean at these times. There were other serious bleaching events throughout the Pacific in 1983.

In 1986, there were a number of moderate bleaching events, worldwide, but in 1987—and this is when most of the attention was focused on this event and it was first recognized as a worldwide event, was due to the 1987 event which was concentrated with the most intense bleaching in the Caribbean region, but there were also moderate to severe bleaching episodes all over the world, as indicated by these circles and ovals in this chart, in 1987.

In 1989 there was very intense bleaching in Jamaica, the most intense and severe bleaching ever recorded in Jamaica, far more than 1987. However, there was only moderate bleaching in the adjacent areas of the Caribbean, and there was no bleaching in the Pacific in 1989.

Now, in 1990, we are seeing severe bleaching again in Jamaica, the Cayman Islands and Puerto Rico, the Bahamas, severe bleaching in the Florida Keys, and there are also reports that bleaching is beginning in Hawaii at this time, and also a report of high temperature mortalities in Okinawa. There will probably be more reports in the Pacific.

It takes us a little while to get reports from those areas than from the Caribbean, but at least in the Caribbean we are certain to have a major event. There is some indication that this might actually become a larger event than 1987.

Our analysis of the first three major bleaching complexes in the article in the "Atoll Research Bulletin" suggested elevated sea water temperatures, compounded by the deterioration of the coral reef environment, caused coral reef bleaching. Preliminary information from the new bleaching complex that is now occurring is in agreement with our original suggestion.

Recent limited field experiments suggest this, as do recent large-scale temperature studies. In the atoll research article we suggested a general model, or simplified model, of the causes of coral reef bleaching.

This is that the sea water temperatures have been gradually increasing. In the 1980's, when all these events have occurred, on top of this elevation we recognize temporary warming events that occur over 1 to 2 to 3 years. In two cases, these were associated with El Niño events. They were occurring at the same time as the bleaching events, and we think this is what caused these temporary warming events. The other two cases were not related to these events.

The third thing that increases the temperature is the normal, seasonal high water temperatures. These events, these complexes, all have what we call a preceding event 1 year before the major event. The reason the preceding event is either less extensive or less severe is because it comes along with the seasonal high water temperatures right at the beginning of this temporary warming event.

The reason a major bleaching event such as 1983, 1987, and now 1990, is the most severe, is because the seasonal warming is on top of the center, or the highest point of the temporary warming event, all of this on top of this general warming trend.

Senator GORE. Basically, you are saying the way the weather system works, there are fluctuations that produce regular increases of temperatures in a pattern. But when the underlying global temperatures increase, then the peaks of the fluctuating temperature pattern get higher each time. Since the stress on the corals occurs at the extreme temperature, if the extremes get higher and occur more frequently, then the stress on the corals is more extensive and more frequent.

Dr. WILLIAMS. Yes, but the short-term warming event, such as El Niño events, have been occurring historically and we have not had the bleaching events. Now, of course, every year we have the seasonal warms, so the interesting thing is that that would place more emphasis on the gradual warming event.

It is also interesting to note that in 1983 there was a severe—the most severe El Niño in 100 years. In 1987, the El Niño event which was associated with the

coral reef bleaching was less, but actually we had more bleaching in 1987. Even though we have no El Niño event this year, there are indications that this may be the severest bleaching event yet.

Also very serious in this recent bleaching is that we are beginning to see mass mortalities of corals. We did not see this in 1987. There were coral deaths. There were partial coral deaths, but now we are seeing mass mortalities of corals in Florida and the Cayman Islands and possibly in parts of the Bahamas, and we do not have accurate records from many other areas, and so this may be much more serious an event this year.

This is one of the species of corals that is dying in the Florida keys now, and here you see a partially bleached colony.

This is a bleached brain coral.

This is a partial recovery of the same colony of coral.

I suggest that there are three things that are needed to examine this problem. First, large-scale monitoring experimental research effort on coral reef bleaching and other marine ecological disturbances, and I believe Ray Hayes and Tom Goreau will discuss this further.

Second, an alert and communications center to compile information and coordinate efforts in understanding major marine ecological disturbances. This is the cheapest component of this effort, but is absolutely essential for any hope of understanding these complex events.

Third, it would be useful to have a reaction team to examine and analyze outbreaks of major ecological disturbances in cooperation with a pool of specialists. It must be in place before each crisis. We cannot just react to something that just happened. It is usually too late. Most of the mystery in major marine ecological disturbances is due to a lack of preparation. Both the specialist and the local field biologist would welcome the aid of any such cooperative team.

Thank you for inviting this testimony and for your interest in this serious problem. We thank Wallop Breau Funds, Sea Grant, and the Caribbean Marine Research Center, for partial support of our efforts.

[The attachments referred to follow:]

# THE DISTRIBUTION AND TIMING OF MAJOR CORAL REEF BLEACHING, POTENTIAL CAUSES, INDICATORS, AND THE BLEACHING CYCLE

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## MAJOR CORAL REEF BLEACHING

Spectacular coral reef bleaching occurred in the Caribbean in 1987, as we detailed in popular articles in OCEANUS (1987), SEA FRONTIERS (1988), and NATURAL HISTORY (1990); and scientific articles in SCIENCE (1987), NATURE (1990), ATOLL RES. BULL. (1990), and others (list available). We received reports of world-wide bleaching for 1979-80, 1982-83 and 1986-88 (maps available). Bleaching also occurred in much of the Caribbean in 1989.

## POTENTAL CAUSES AND INDICATORS OF GLOBAL CHANGES

We have suggested that increasing temperatures of the 1980s, short-term warming events, and seasonal highs, force seawater temperatures to the point of causing major coral reef bleaching events. Deterioration of coral reefs may have also reduced reef organism's resilience or resistence to the bleaching process. Coral reef organisms live in waters that are almost as hot as they can withstand. Even slight changes can be important in this tropical environment. Coral reefs may be highly sensitive indicators of global changes.

## THE CORAL REEF BLEACHING CYCLE

World-wide bleaching complexes occurred in 1979-80, 1982-83, 1986-88, and we expect will in 1989-90. None are known prior to the 1980s. Major bleaching events occurred in 1980, 1983, 1987 and will possibly in 1990. Preceding bleaching events occurred in 1979, 1982, 1986 and we suggested in 1989. Preceding and major events form bleaching complexes or cycles. Preceding events can be used to predict major events. We are predicting another major bleaching event for 1990.

## POSSIBLY RELATED MAJOR MARINE ECOLOGICAL DISTURBANCES (MMED)

Regional-wide mass mortalities of marine fishes occurred in 1980, black long-spined sea urchins in 1983-84, acroporid corals and recurring mortalities of herrings throughout the 1980s. Many other MMEDs have similarly occurred in other regions in the 1980s. These problems may be interrelated, may share causes, and may be additional indicators of global changes.

## ASSOCIATION OF MARINE LABORATORIES OF THE CARIBBEAN SERVICES

The Executive Board of the AMLC approved the following statement during their 19 June 1990 meeting: "The Association of Marine Laobratories of the Caribbean (AMLC) recognizes the necessity to develop long-term monitoring of marine environmental variables implicated as possible causes of mass coral reef bleachings and offers its resources and expertise to such a regional effort in the Caribbran Basin in cooperation with other international organizations in the region." The Association's goals include the initiation and cooridination of its 27 Institutional Member Marine Laboratories in the Greater Caribbean Region in cooperative research efforts. The AMLC hopes to be a useful and positive forum and structure for the process of examining and understanding this problem. As Executive Director of the Association, I would like to welcome the use of the Association, member laboratories, and our individual scientists, to serve in the resolution of this problem.

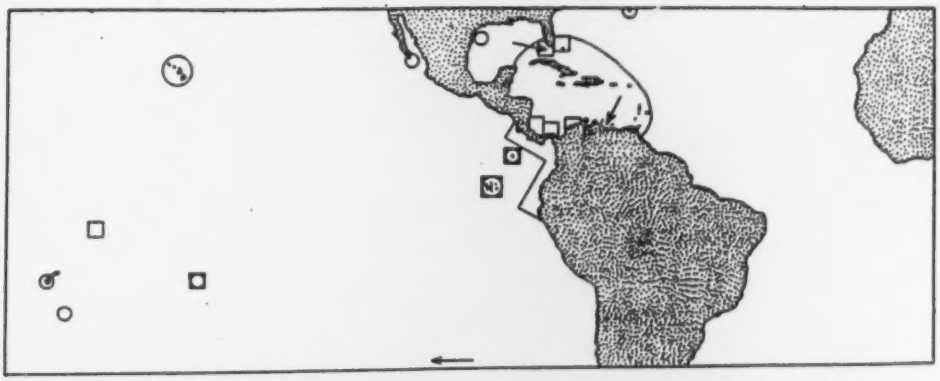


Figure (Part 1) The world from 33°S to 33°N, Part 1: Central Pacific to Atlantic. 1979-80 Coral Reef Bleaching Sites Marked with Arrows, the 1982-83 with Squares and Rectangles, the 1986-88 in Circles and Elipses.

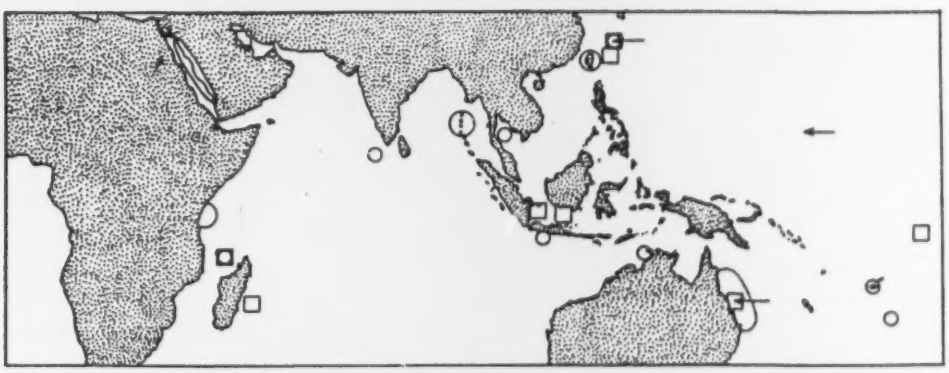


Figure (Part 2) The world from 33°S to 33°N, Part 2: Eastern Atlantic to Western Pacific. 1979-80 Coral Reef Bleaching Sites Marked with Arrows, the 1982-83 with Squares and Rectangles, the 1986-88 in Circles and Elipses.

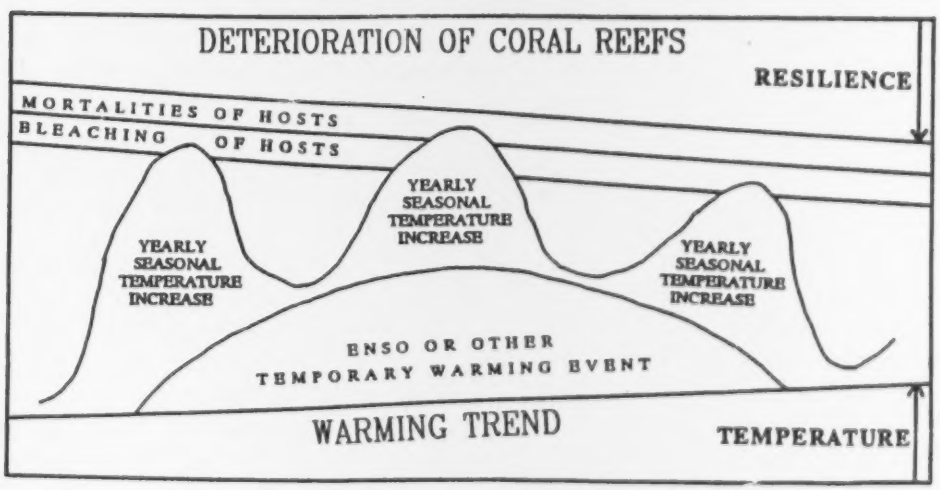


Table 1. Species that Bleached in 1990

| Species | Location | Date bleached | Source |
|---|---|---|---|
| **SPONGES** | | | |
| *Anthosigmella varians* | Aguadilla, Puerto Rico | October | Goenaga PC |
| *Chondrilla nucula* | La Parguera, Puerto Rico | September | This paper |
| *Mycale laevis* | La Parguera, Puerto Rico | September | This paper |
| *Xestospongia muta* | La Parguera, Puerto Rico | September | This paper |
| **HYDROCORALS** | | | |
| *Millipora alcicornis* | Hens and Chickens Reef, Plantation Key, FL | August | Hudson PC |
| | Sands Key, just north of Key Largo | September | Glynn PC |
| | West Flower Garden Bank off Galveston, Texas | August-September | Gittings PC |
| | La Parguera, Puerto Rico | September | This paper |
| *Millipora complanata* | Looe Key National Marine Sanctuary Big Pine Key, FL | August | Causey PC |
| | La Parguera, Puerto Rico | September | This paper |
| *Millipora squarosa* | La Parguera, Puerto Rico | September | This paper |
| *Millipora* sp. | St. John, U.S. Virgin Islands | May | Rogers PC |
| | St. John, U.S. Virgin Islands | Sept-Oct | Rogers PC |
| | Looe Key National Marine Sanctuary Big Pine Key, FL | July-August | Causey PC |
| | La Parguera, Puerto Rico | September | Morelock PC |
| | off central-east Andros Island, Bahama Islands | August | Kane PC |
| | East Flower Garden Bank off Galveston, Texas | August-September | Gittings PC |
| | Stetson Bank, off Texas | September | Gittings PC |
| | Grand Cayman Island | July | Hayes PC |
| **OCTOCORALS** | | | |
| *Erythropodium caribbaeorum* | Mona Island, Cayo Pajaros, near wreck of M/V Regina | February | Vicente PC |
| *Eunecia succinea* | La Parguera, Puerto Rico | September | This paper |
| *Eunicea* sp. | La Parguera, Puerto Rico | September | This paper |
| *Gorgonia ventalina* | La Parguera, Puerto Rico | September | This paper |
| *Muriciapsis flavida* | La Parguera, Puerto Rico | September | This paper |
| *Plexaurella dichotoma* | La Parguera, Puerto Rico | September | This paper |
| *Plexaurella* sp. | La Parguera, Puerto Rico | September | Yoshioka PC |
| *Pseudoplexaura* sp. | La Parguera, Puerto Rico | September | This paper |
| *Pseudopterogorgia acerosa* | La Parguera, Puerto Rico | September | This paper |
| *P. americana* | La Parguera, Puerto Rico | September | This paper |
| *P. bipinnata* | La Parguera, Puerto Rico | September | This paper |
| *Pseudopterogorgia rigida* | La Parguera, Puerto Rico | September | This paper |
| **ANEMONES** | | | |
| *Condylactis gigantea* | La Parguera, Puerto Rico | September | This paper |
| *Labrunea danae* | La Parguera, Puerto Rico | September | This paper |
| *Phymanthus crucifer* | La Parguera, Puerto Rico | September | This paper |
| *Ricordea florida* | La Parguera, Puerto Rico | September | This paper |

| | | | |
|---|---|---|---|
| **ZOOANTHIDS** | | | |
| Palythoa caribbea | Mona Island, Cayo Pajaros, near M/V Regina | February | Vicente PC |
| | Looe Key National Marine Sanctuary Big Pine Key, FL | July-August | Causey PC |
| | La Parguera, Puerto Rico | September | Rosado PC |
| | Guayama and Salinas, Puerto Rico | October | Cianchini PC |
| | La Parguera, Puerto Rico | September | This paper |
| | off Havana, Cuba | June | This paper |
| Parazoanthus parasiticus | La Parguera, Puerto Rico | September | This paper |
| Zoanthus sociatus | La Parguera, Puerto Rico | September | This paper |
| Zoanthus sp. | La Parguera, Puerto Rico | September | Rosado PC |
| | Grand Cayman Island | July | Hayes PC |
| **STONY CORALS** | | | |
| Acropora cervicornis | Looe Key National Marine Sanctuary Big Pine Key, FL | July-August | Causey PC |
| | Guayama and Salinas, Puerto Rico | October | Cianchini PC |
| | La Parguera, Puerto Rico | September | This paper |
| | Veracruz, Mexico | June-July | Tunnell PC |
| Acropora palmata | La Parguera, Puerto Rico | September | Lopez PC |
| | Looe Key National Marine Sanctuary Big Pine Key, FL | July-August | Causey PC |
| | La Parguera, Puerto Rico | September | This paper |
| | Veracruz, Mexico | June-July | Tunnell PC |
| Acropora sp. | Jamaica | August | Goreau PC |
| Agaricia agaricites | Hens and Chickens Reef, Plantation Key, FL | August | Hudson PC |
| | East Flower Garden Bank off Galveston, Texas | August-September | Gittings PC |
| | La Parguera, Puerto Rico | September | This paper |
| | British Virgin Islands The Indians and Truck Reef | July | Peters PC |
| | off Havana, Cuba | June | This paper |
| Agaricia lamarki | La Parguera, Puerto Rico | September | This paper |
| Agaricia tinuifolia | south Florida | October | Ferrer PC |
| Agaricia sp. | St. John, U.S. Virgin Islands | May | Rogers PC |
| | Jamaica | August | Goreau PC |
| | Stetson Bank, off Texas | September | Gittings PC |
| | south coast of Cuba | June | Gotera PC |
| Brain coral | Guayama and Salinas, Puerto Rico | October | Cianchini PC |
| Colpophyllia natans | Hens and Chickens Reef, Plantation Key, FL | August | Hudson PC |
| | Looe Key National Marine Sanctuary Big Pine Key, FL | July-August | Causey PC |
| | West Flower Garden Bank off Galveston, Texas | August-September | Gittings PC |
| | East Flower Garden Bank off Galveston, Texas | August-September | Gittings PC |
| | La Parguera, Puerto Rico | September | This paper |
| | Hol Chan Reserve, Belize | January | Aiken PC |

| | | | |
|---|---|---|---|
| Dendrogyra cylindratus | La Parguera, Puerto Rico | September | This paper |
| Dendrogyra sp. | Jamaica | August | Goreau PC |
| Dichocoenia stokesii | Looe Key National Marine Sanctuary Big Pine Key, FL | July-August | Causey PC |
| | off Havana, Cuba | June | This paper |
| Diploria clivosa | Looe Key National Marine Sanctuary Big Pine Key, FL | July-August | Causey PC |
| | La Parguera, Puerto Rico | September | This paper |
| Diploria labyrinthiformes | Hens and Chickens Reef, Plantation Key, FL | August | Hudson PC |
| | Looe Key National Marine Sanctuary Big Pine Key, FL | July-August | Causey PC |
| | Bermuda | | Gerstle PC |
| | La Parguera, Puerto Rico | September | This paper |
| | British Virgin Islands The Indians and Truck Reef | July | Peters PC |
| Diploria strigosa | Looe Key National Marine Sanctuary Big Pine Key, FL | July-August | Causey PC |
| | East Flower Garden Bank off Galveston, Texas | August-September | Gittings PC |
| | Bermuda | | Gerstle PC |
| | La Parguera, Puerto Rico | September | This paper |
| Diploria sp. | Mona Island, Cayo Pajaros, near M/V Regina | February | Vicente PC |
| | Jamaica | August | Goreau PC |
| | La Parguera, Puerto Rico | September | Morelock PC |
| Eusmilia fastigiata | La Parguera, Puerto Rico | September | This paper |
| Favia fragum | Looe Key National Marine Sanctuary Big Pine Key, FL | July-August | Causey PC |
| | La Parguera, Puerto Rico | September | This paper |
| Helioceris cuculata | La Parguera, Puerto Rico | September | This paper |
| Meandrina meandrites | Looe Key National Marine Sanctuary Big Pine Key, FL | July-August | Causey PC |
| | Guayama and Salinas, Puerto Rico | October | Cianchini PC |
| | La Parguera, Puerto Rico | September | This paper |
| | off Havana, Cuba | June | This paper |
| Montastrea annularis | Mona Island, Cayo Pajaros, near M/V Regina | February | Vicente PC |
| | St. John, U.S. Virgin Islands | May | Rogers PC |
| | Culebra Island, Puerto Rico | May | Hall PC |
| | Hens and Chickens Reef, Plantation Key, FL | August | Hudson PC |
| | Saba Marine Park, Saba, Netherland Antilles | July | Walker PC |
| | Looe Key National Marine Sanctuary Big Pine Key, FL | July-August | Causey PC |
| | La Parguera, Puerto Rico | September | This paper |
| | N.W. of Grand Bahama Island Bahama Islands | August | Perrine PC |
| | West Flower Garden Bank off Galveston, Texas | August-September | Gittings PC |
| | East Flower Garden Bank off Galveston, Texas | August-September | Gittings PC |

| | | | |
|---|---|---|---|
| | Bermuda | | Gerstle PC |
| | Veracruz, Mexico | June-July | Tunnell PC |
| | Grand Cayman Island | July | Hayes PC |
| | Bimini and Cay Sal Bank Bahama Islands | July | Perrine PC |
| Montastrea cavernosa | Looe Key National Marine Sanctuary | | |
| | Big Pine Key, FL | July-August | Causey PC |
| | West Flower Garden Bank off Galveston, Texas | August-September | Gittingg PC |
| | East Flower Garden Bank off Galveston, Texas | August-September | Gittings PC |
| | La Parguera, Puerto Rico | September | This paper |
| Montastrea sp. | Jamaica | August | Goreau PC |
| Musa angulosa | La Parguera, Puerto Rico | September | This paper |
| Mycetophylia alicia | La Parguera, Puerto Rico | September | This paper |
| Pocillapora sp. | Hawaii | September | Choquette PC |
| Porites sp. | Jamaica | August | Goreau PC |
| Porites astreoides | Hens and Chickens Reef, Plantation Key, FL | August | Hudson PC |
| | Looe Key National Marine Sanctuary Big Pine Key, FL | July-August | Causey PC |
| | La Parguera, Puerto Rico | September | This paper |
| | British Virgin Islands The Indians and Truck Reef | July | Peters PC |
| Porites porites | Hens and Chickens Reef, Plantation Key, FL | August | Hudson PC |
| | Looe Key National Marine Sanctuary Big Pine Key, FL | July-August | Causey PC |
| | La Parguera, Puerto Rico | September | Morelock PC |
| | Hol Chan Reserve, Belize | January | Aiken PC |
| Siderastrea siderea | Saba Marine Park, Saba, Netherland Antilles | July | Walker PC |
| | Sands Key, just north of Key Largo | September | Glynn PC |
| | Looe Key National Marine Sanctuary Big Pine Key, FL | July-August | Causey PC |
| | La Parguera, Puerto Rico | September | Morelock PC |
| | Truck Reef, British Virgin Islands | July | Peters PC |
| Siderastrea radians | Looe Key National Marine Sanctuary Big Pine Key, FL | July-August | Causey PC |
| Siderastrea lobates | off Havana, Cuba | June | This paper |
| Siderastrea sp. | Jamaica | August | Goreau PC |
| | N.W. of Grand Bahama Island Bahama Islands | August | Perrine PC |
| | Guayama and Salinas, Puerto Rico | October | Cianchini PC |
| Stephanocoenia michilinii | La Parguera, Puerto Rico | September | This paper |

Table 2: Coral Reef Bleaching in 1990, Bout 2 (July-? 1990): Major Bleaching Event

| LOCATION | DATE BEGAN | DATE SEVERE | SOURCE |
|---|---|---|---|
| **C A R I B B E A N:** | | | |
| **CUBA** | | | |
| south coast | early June | - | Gotera PC |
| north coast | mid-June | - | This paper |
| **NETHERLAND ANTILLES** | | | |
| Saba | early July | - | Walker PC |
| **CAYMAN ISLANDS** | | | |
| all islands | mid-July | mid-August | Hayes PC |
| **JAMAICA** | | | |
| north coast | mid-August | - | Goreau PC |
| **PUERTO RICO** | | | |
| Salinas area | September | - | Cianchini PC |
| Guanica area | September | - | Canales PC |
| La Parguera area | early Sept. | mid-Sept. | This Paper |
| | | mid-Sept. | Yoshioka PC |
| | | mid-Sept. | Rosado PC |
| | | mid-Sept. | Lopez PC |
| | | late Sept. | Morelock PC |
| entire coastal areas | - | late-Sept. | Goenaga PC |
| **BRITISH VIRGIN ISLANDS** | | | |
| The Indians (reef) | late June | - | Peters PC |
| Truck Reef | late June | - | Peters PC |
| **U. S. VIRGIN ISLANDS** | | | |
| St. John | late Sept. | - | Rogers PC |
| **G U L F O F M E X I C O:** | | | |
| **MEXICO** | | | |
| Veracruz area | late June | - | Tunnell PC |
| **TEXAS, USA** | | | |
| Flower Garden Banks | July | mid-Sept. | Gittings PC |
| **A T L A N T I C:** | | | |
| **BRAZIL** | | | |
| northeast coast | - | early in year[2] | Duarte-A. PC |
| **FLORIDA, USA** | | | |
| Looe Key | late July | mid-August | Causey PC |
| Hens & Chickens Reef | late August | - | Hudson PC |
| Sands Key | mid-Sept. | - | Glynn PC |
| South Florida | early Oct. | - | Ferrer PC |
| **BERMUDA** | | | |
| Bermuda | mid-August | - | Cook PC |
| | - | - | Gerstle PC |
| **BAHAMAS** | | | |
| Bimini area | mid-July | - | Perrine PC |
| Cay Sal Bank | mid-July | - | Perrine PC |
| Lee Stocking Island | August | late Sept. | Wicklund PC |
| Andros Island | mid-August | - | Kane PC |
| Grand Bahama Island | late August | - | Perrine PC |
| **P A C I F I C:** | | | |
| Hawaii | mid-Sept. | - | Choquette PC |
| Okinawa | summer (very few colonies) | | Glynn PC |
| | late summer[1] | - | Hasegawa PC |

[1]Severe high temperature damage to reef organisms(?)
[2]southern hemisphere warm water period.

Table 3: Coral Reef Bleaching in 1990, Bout 1 (May 1990): Minor Bleaching Bout

| LOCATION | DATE BEGUN | SEVERITY | SOURCE |
|---|---|---|---|
| **A T L A N T I C:** | | | |
| **FLORIDA, USA** | | | |
| Dry Tortugas | early May | no bleaching | Colin PC |
| Loggerhead Key | early May | no bleaching | Colin PC |
| **C A R I B B E A N:** | | | |
| **U. S. VIRGIN ISLANDS** | | | |
| St. John | late Feb. | no bleaching | Hardy PC |
| | early May | widespread, mild | Rogers PC |
| **PUERTO RICO** | | | |
| Mona Island | February | restricted[1] | Vicente PC |
| Culebra Island | mid-May | mild | Hall PC |
| La Parguera area | mid-Feb. | mild | Morelock PC |
| | early May | mild | Lopez PC |
| SW shelf edge | early May | no bleaching | This Paper |
| **CAYMAN ISLANDS** | | | |
| Grand Cayman | April | not stated | Perrine PC |
| | early May | extensive | Goreau PC |
| all Cayman Islands | early May | extensive | Hayes PC |
| **COLOMBIA** | | | |
| Isla del Rosario | early May | not quantified | Obregon PC |
| **ST. VINCENT** | May | not stated | Schoen PC |
| **LEEWARD ISLANDS** | | | |
| Antigua | early March | no bleaching | Hardy PC |
| Guadeloupe | early March | no bleaching | Hardy PC |
| **E A S T E R N P A C I F I C:** | | | |
| **COLOMBIA** | | | |
| Isla Gorgona | early May | not quantified | Garms-C. PC |
| | mid-May | no bleaching | Botero & Bula PC |
| Santa Marta | May | no bleaching | Zea PC |

[1]Intense bleaching but limited to the immediate vicinity of the wreck of the R/V Regina. This may not be related to bout #1.

Table 4: Coral Reef Bleaching in 1989, Bout 2[1] Mid- to Late 1989 Preceding Bleaching Event

| LOCATION | DATE BEGUN | SEVERITY | SOURCE |
|---|---|---|---|
| **C A R I B B E A N:** | | | |
| **JAMAICA** | | | |
| north coast | late Sept. | moderate | Goreau PC |
| | mid-Oct. | severe, widespread | Goreau PC |
| | late Oct. | very severe | Sebens PC |
| | early Nov. | severe | Glazer PC |
| | mid-Oct. | moderate | Smit PC |
| | late Dec. | severe | Risk PC |
| south coast | October | mild | Mendes PC |
| Port Royal Keys | January(90) | mild | Goreau PC |

| | | | |
|---|---|---|---|
| **CAYMAN ISLANDS** | | | |
| Grand Cayman | late Oct.<br>November | widespread<br>moderate | Byrnes PC<br>Hayes & Bush PC |
| Little Cayman | October | moderate | Perrine PC |
| Cayman Brac | October | moderate | Perrine PC |
| **PUERTO RICO** | | | |
| eastern coast | mid-Oct. | mild | Vicente PC |
| western coast | late Oct. | mild | Goenaga PC |
| southwest coast | mid-Sept.<br>mid-Sept.<br>late Oct.<br>late Oct. | mild<br>mild<br>mild<br>mild | This paper<br>Goenaga PC<br>Morelock PC<br>Yoshioka PC |
| Culebra Island | mid-Oct. | mild | Vicente PC |
| Vieques Island | mid-Oct.<br>early Dec. | mild<br>moderate | Vicente PC<br>Vicente PC |
| **CUBA** | | | |
| southeast coast | Oct.-Nov.<br>Oct.-Nov. | moderate<br>moderate | Soberats-B. PC<br>Ruiz-B. PC |
| **U. S. VIRGIN ISLANDS** | | | |
| St. Thomas | mild | This paper | |
| **BRITISH VIRGIN ISLANDS** | | | |
| Tortola | late Oct. | mild | Keil PC |
| **NETHERLAND ANTILLES** | | | |
| Curacao | mid-Nov. | mild | Sybesma PC |
| **BARBADOS** | | | |
| west coast | late Nov.<br>Fall | mild<br>mild | Ballantine PC<br>Oxenford PC |
| **COLOMBIA** | | | |
| Isla del Rosario | Fall | very mild | Bohorquez PC |
| **BELIZE** | | | |
| Barrier Reef | January(90) | moderate | Aiken PC |
| **PANAMA** | | | |
| San Blas Islands | November | moderate | Knowlton PC |
| **A T L A N T I C:** | | | |
| **FLORIDA KEYS** | | | |
| Looe Key | early Sept.<br>late Sept. | mild<br>moderate | Causey PC<br>Causey PC |
| Western Sambo Reef Key West | Sept. | mild | Jaap PC |
| lower Florida Keys | Sept. | mild | Causey PC |
| middle Florida Keys | Sept. | moderate | Causey PC |
| upper Florida Keys | Sept. | mild | Causey PC |
| **SOUTH FLORIDA** | | | |
| south Florida | late Nov. | very mild | Poyer PC |
| **BAHAMAS** | | | |
| Lee Stocking Is. | early Sept. | not stated | Wicklund PC |
| Lost Reef | early Dec. | mild | Hayes PC |
| New Providence Island | early Dec. | mild | Hayes PC |
| **P A C I F I C** | | | |
| **TAIWAN** | | | |
| limited area[2] | June-Sept. | severe | Dai PC |

[1]the first bleaching bout in 1989 occurred from March to April and involved mild bleaching in St. Thomas, Mona Island and southwestern Puerto Rico, and moderate bleaching in the Gulf of California (Williams and Bunkley-Williams 1990).
[2]influeanced by a nuclear power plan outfall.

Table 5: **New Reports on Previous Bleaching Events**

| LOCATION | DATES | COMMENTS | SOURCE |
|---|---|---|---|
| **C A R I B B E A N** | | | |
| Barbados | for a number of years | - | Oxenford PC |
| Cuba | 1979-1989 | mild-severe | Ibarra PC |
| **A T L A N T I C** | | | |
| Brazil | early 1986 | moderate | Duarte-A. PC |
| (northeast) | early 1987 | moderate | Duarte-A. PC |
| **P A C I F I C** | | | |
| **AUSTRALIA** | | | |
| Cooktown to Capricorn Islands | Jan.-March 1987 | severe | Grimes PC |
| Darwin area | early 1987 | severe | Alderslade PC |
| Darwin area | Feb. 1988 | severe | Alderslade PC |
| Darwin area | Feb. 1982 | moderate | Alderslade PC |
| **MALDIVES** | 1987 | severe(anemones, soft corals) | Risk PC |
| **PHILIPPINES** | recent years | moderate | Yap PC |
| | recent years | not recorded | Veron PC |

Table 6: **Black Band Disease Outbreaks or Increases Following Coral Reef Bleaching Events in the Caribbean**

| LOCATION | DATES | AMOUNT | SOURCE |
|---|---|---|---|
| Belize | Jan. 1990 | severe[1] | Aiken PC |
| Colombia | | | |
| Cartagena | 1988-1989 | severe | Goreau PC |
| Jamaica | 1989 | not occurring | Goreau PC |
| Puerto Rico | | | |
| west coast | mid-1989 | moderate | Goenaga PC |
| southwest | 1988-1989 | mild | This paper |
| U. S. Virgin Islands | | | |
| St. Thomas | 1988 | moderate | This paper |

[1]severe white band disease also occurred.

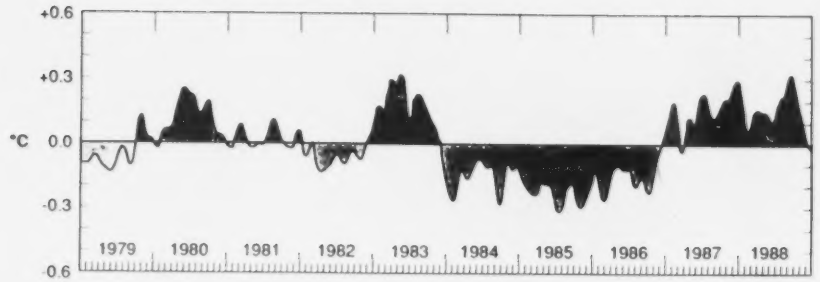
Table 7: **Periods of No Coral Reef Bleaching**

| LOCATION | TIME PERIOD | SOURCE |
|---|---|---|
| **C A R I B B E A N:** | | |
| Cuba | 1987-1988[1] | Gotera PC |
| Panama[2] | November 1989 | Guzman PC |
| **A T L A N T I C:** | | |
| **BRAZIL** | | |
| Archipeligo of Fernando de Noronha | 1985 & 1988 | Rodrigues PC |
| Abrolhos Reefs | 1980s | Rodrigues PC |
| southern region | recorded history | Rodrigues PC |
| **P A C I F I C:** | | |
| Diego Garcia | recorded history(?) | Walker PC |
| Hawaii | 1989 | Choquette PC |
| Kwajaleiu | last 30 years | Johnson PC |
| Kenya | August 1988 through August 1990 | McKenzie PC |
| Mariana Islands | 1988 & 1989 | Donaldson PC |
| Okinawa | 1989 | Walker PC |
| Singapore | 1977 through 1988 | Ming PC |
| Solomon Islands | recorded history to January 1990 | Munro PC |
| Tiawan | prior to 1987(?) | Dai PC |

[1]No sponges bleached although stony corals bleached.
[2]No bleaching on the inshore reefs, although it was occurring offshore in the San Blas Islands.

NASA
Marshall Space Flight Center — The University of Alabama in Huntsville

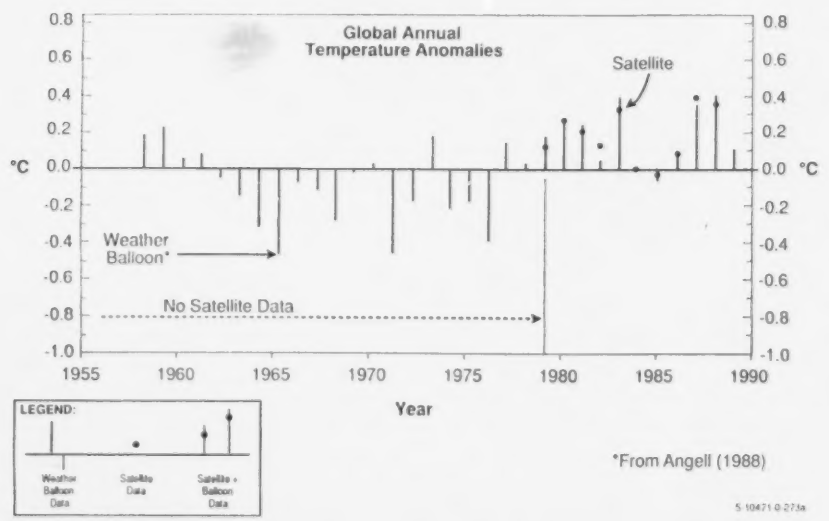
**Satellite**
**Global Tropospheric Temperature Trends**
**1979 - 88**




From Spencer and Christy (1990)

FIGURE 1

**Satellites Agree With Weather Balloon Data**




*From Angell (1988)

FIGURE 2

S 10471-0 27Sa

Senator GORE. Thank you very much. Our final witness on this panel is Thomas Goreau, senior scientist with the Discovery Bay Marine Laboratory at the University of the West Indies in Discovery Bay, Jamaica.

## STATEMENT OF THOMAS J. GOREAU, SENIOR SCIENTIST, DISCOVERY BAY MARINE LABORATORY, UNIVERSITY OF THE WEST INDIES, JAMAICA

Mr. GOREAU. Thank you.

I am also president of the Global Coral Reef Alliance, which is an organization of scientists and others who are concerned about the fact that all the reefs we study everywhere in the world appear to be undergoing degradation, and yet it is treated by the public, policymakers, and funding agencies largely as a local phenomenon. We are attempting to try to get some of the information out on this and to try to address some of these issues.

I have been involved in research in Jamaica all my life. My father pioneered the use of SCUBA as a scientific research tool and we have been studying the reefs in Jamaica constantly for the last 40 years. When I was small, we had large fish and many species. Now we have a handful of species of fish, and they are all small.

The result of that is that the natural checks on the populations of most marine organisms has disappeared. In addition, we have had increasing deforestation which has steadily increased the soil that has washed onto the reefs and other corals.

We do not treat our sewage around every population center and tourist center. There is a ring of dead and dying reef where algae are undergoing prolific growth due to the nutrients coming in in sewage, and so we are smothering the reef.

So we have seen this degradation steadily occurring over 40 years, but we have never before, until 1987, seen the sort of mass bleaching phenomena that have occurred recently. They have occurred in 3 of the last 4 years. We had seen bleaching before, but it had always been strictly local, usually confined to shallow reefs and downstream of river mouths or in the way of hurricane floods.

The bleaching we have seen in the last 3 years has had greater effect on the growth of the reef than all the other forms of deterioration. It is truly alarming. When it first occurred in 1987, really we did not know what the cause was. Part of the problem is that despite decades of efforts there has never been any source of support for long-term monitoring of something as elementary as temperature.

There has been funding, really, for what I refer to as tourist science. Short-term visits, in and out, but not building the long-term research that is needed to understand these events or to develop sustainable management of the ecosystems: so we did not have any long-term temperature database.

What we have tried to do, and what I am going to present here, is a study of the NOAA satellite sea surface temperature records for the Caribbean region. Let me say something about that data. It is largely not available in accessible form. There are two databases, one from a satellite that is in—a synchronous orbit. It is very high up. It stays stationary over the earth.

Global coverage is obtained, and is published by NOAA in the form of monthly average summaries. The resolution in terms of the spatial area that they can see is fairly poor. We looked at that database, for bleaching years, where we were in the water and had temperature measurements in the water, it did not correlate very closely—not closely enough—and so we did not use that data.

What we used instead was another NOAA satellite database that was based upon a polar orbiting satellite. That was one that comes whipping up around the South Pole, up to the North Pole, and covers every part of the earth twice a day. The data is logged twice a week.

We found, in comparing those satellite temperatures to 5 years of in-the-water records in Jamaica that it agreed very closely. However, the satellite data was a little bit too low by a few tenths of a degree centigrade, but otherwise very close, and so that is the database we used, and it was very high resolution in terms of the spatial resolution, and it seems pretty accurate.

I must emphasize, though, that what we are seeing in this record are open water temperatures off-shore. That is not the same temperature that the coral is

seeing, which is why it is not a substitute for in-the-water long-term measurements. However, it does provide a regional database to be able to compare different locations for different times.

For this, data has been accumulated since May of 1980. We have looked at every single image that has been taken of the Caribbean in that period of time. I will show you—I would like to show you slides, and I would prefer to stand there because I will have to point out things.

Senator GORE. Fine.

[Slides shown]

Mr. GOREAU. This shows a pattern of surface currents in the Caribbean region. The water comes in this direction. Here is Jamaica. It goes past here, forms a loop current which turns into the Gulf Stream and goes shooting out. What we have done is to look at the records for Puerto Rico, Jamaica, Cayman, Cozumel, Florida, the Bahamas, and Bermuda, and so we are sort of following the water path as it goes around.

Here we have computed the monthly averages for 10 years in Puerto Rico. This would be the entire 1980's surface water temperatures. As I mentioned, this does not reflect the reef temperature, because the reefs can heat up a great deal if water does not circulate well with the open ocean.

But by and large, the reefs in Puerto Rico, Jamaica, and the Cayman, are right on the edge of a submarine precipice and so they are exposed to open ocean temperatures fairly closely, but in Florida and the Bahamas there are large shallow shelves. They do not circulate well and so those can heat up quite a bit higher, probably, than the open water temperature—certainly higher. But we do not have that in-shore data, so we are looking at regional changes in open water temperature.

In Puerto Rico, bleaching is indicated by the square. Now, this data ends in May of 1990, and of course since then the temperature has come up and there is new mass bleaching in Puerto Rico, with temperatures up here. But what you see is the one bleaching event in this period of time that occurred in the 1980's, and Puerto Rico was in the highest, single temperature, monthly average temperature, in that 10-year period.

For Jamaica, 1987 was the first bleaching that was unusual. As I mentioned before the satellite values are a little too low. The actual in-the-water temperatures were 30 degrees and not 29.6, as indicated here. There was mass bleaching in Jamaica. It lasted for 10 months.

I measured the growth of whole populations of corals in the field. I have been doing that for years. Those corals did not grow in that 10-month period. They did not reproduce. Somehow they managed to survive, but they simply did not grow in that period of time.

That was the most prolonged high-temperature period. There were other months and years where individual months got nearly as hot, but here it stayed up near 30 degrees for 4 months. That was unprecedented.

Senator GORE. So you have taken the satellite temperature record and compared it to the occurrence of the bleaching events?

Mr. GOREAU. Yes.

Senator GORE. There is, in fact, a precise correlation?

Mr. GOREAU. That is right.

Senator GORE. When the temperature gets the highest, the bleaching occurs?

Mr. GOREAU. That is right. That is correct. However, that temperature differs from place to place. For instance, a lower temperature is required to cause bleaching in Bermuda than in Jamaica, and so it is not a single magic number.

Senator GORE. Because these organisms have adapted, and so forth?

Mr. GOREAU. Yes. In 1989, we had the highest temperatures ever reported in Jamaica.

Senator GORE. Up until this year.

Mr. GOREAU. Up until this year, that is correct. In May 1989, there was the worst bleaching we had seen anywhere in the Caribbean. Every place I dived in the north coast of Jamaica, about 80 percent or so of the corals were bleached. That was the hottest year ever, until this year, and this year is up here some place, and the bleaching is worse than it was in 1989; at least, looking at the beginnings of it.

Cayman, the picture is identical to Jamaica. Mass bleaching in 1987, 1989. Those were the two hottest years on record.

In Cozumel the pattern is quite different, because Cozumel is influenced by the water coming up from the coast of Central America. It is probably influenced by higher rainfall and runoff from coastal regions. The only known mass bleaching at Cozumel was in 1987, which was the hottest temperature on record. We are suspicious that there might have possibly been bleaching this year, because it was pretty warm, but we know of no bleaching records then, but again, 1987 was the highest temperature at Cozumel.

Florida, there was a major mass bleaching in 1987 and 1989, which was not as bad as in 1987. Those are the two hottest years. This one here, there was a small bleaching event that Walt Jaap found in 1984, or 1983, and that is not very high in terms of the monthly averages, compared to these ones later. However, it contains the single highest daily temperature that we saw in Florida until this year.

So that one was a local event, as there were certain regions that were more influenced by higher temperature waters. But again, the highest temperatures were there (1987), and again (1989), until this year, which is not on this graph.

Bahamas, bleached in 1987 and 1989, the two hottest years on record.

Bermuda, the pattern is quite different. Mass bleaching was only in 1988. Different water masses and all of that. That was the hottest year on record in Bermuda, and so both the spatial and temporal pattern of bleaching mimics that of temperature. Jamaica and Cayman in 1989 were hotter than any other part of the Caribbean. It seems to have been a regional hot spot that developed in that area, and bleaching was more intense. So we are pretty satisfied with this; there is a precise correlation between bleaching and temperature.

Now, the other question that interests us here is, well, are temperatures in fact rising, on the average, in the Caribbean?

What we have done is, we have taken the data and we have subtracted the long-term average over the 10-year period. These are the average seasonal variations in these locations. Jamaica is the warmest, Bermuda is the coolest. Subtract those off, and then what we look at are the differences from the average behavior. I will show that in the next slide, please.

For each of the locations, these are the deviations from the average for each month, all through this 10-year period. Puerto Rico, there is no significant trend in the long-term temperatures. There are hot years. That point was in 1987, and this year will be up here, but at least statistically there is absolutely no trend there.

Jamaica, statistically a significant increase.

Cayman, just on the edge of being statistically significant. I must mention, this was somewhat unexpected because it is very difficult to see small changes superimposed on large, seasonal variations. One needs a lot of data to be able to say, with statistical confidence, that a small change has in fact occurred. Ten years of data is about what you need for the kind of temperature variation we see in the Caribbean. For other areas of the world, it is not enough. Where the

seasonal variation is larger, it is simply harder to see that small change. Cayman is just on the edge of being statistically significant.

Cozumel, no significant change. I said before that the water temperature patterns there are really different than the others.

Florida, significant increase in temperature.

The Bahamas, significant increase in temperature.

Bermuda, highly significant increase in temperature over the decade. I am not going to show the transparency here, but ignoring Cozumel and Puerto Rico, which do not show significant increases, the other places have, over the decade, raised their average temperatures between about 4/10ths and 1 degree centigrade over that 10-year period.

This is temperature data from Hawaii for a 10-year period showing the maximum temperatures that have been reached. This was, of course, in the Pacific. That is a statistically significant increase, once again. Mass bleaching occurred there in 1986, and we understand it is happening this year as well.

It does seem to be—although we have not been able to examine the same sort of databases yet in other locations, other than the Caribbean, we seem to be seeing similar patterns. Now, because we have looked really only at the Caribbean record, we can say something about regional warming. We have not examined global databases.

Regional warming can occur for a number of reasons other than global changes. Shifts in the currents and the winds, for instance, or the mixing of the water can affect local temperatures. The data to distinguish that from truly global warming we do not have available.

However, the fact that we are seeing the same sort of bleaching phenomena occurring in the Indian Ocean and the Pacific is implying that, like the Caribbean, those areas are now beginning to be pushed over the maximum temperature tolerance limit of corals, and this appears to be a worldwide phenomenon.

So while we have to be a little agnostic, if you will, on whether this is global change, it certainly does look like that to us. We cannot say anything about the greenhouse effect. Corals are not responding directly to CO2 in the atmosphere, they are responding directly to water temperatures immediately around them, but personally, I do not doubt there is a connection. But we could not prove that from this database alone.

Thank you.

[The statement follows:]

STATEMENT OF THOMAS GOREAU, PRESIDENT, GLOBAL CORAL REEF ALLIANCE

My name is Tom Goreau. I am President of the Global Coral Reef Alliance, a newly formed non profit organization of scientists and others concerned about coral reef degradation, which aims to educate the public and policy makers in order to effect action to protect coral reefs. The Alliance will emphasize the ecological, environmental, and economic importance of reef ecosystems, the threats to them, policies which could protect and restore them, and raising funds for long-term conservation, environmental monitoring, and research into sustainable management, including mariculture and reef restoration. I am also a scientific researcher at the Discovery Bay Marine Laboratory in Jamaica, where I have been involved with research on coral reefs since childhood: my late father pioneered the use of SCUBA as a scientific research tool, and he and his successors have studied Jamaican reefs for 40 years, the longest anywhere. It is because of this lifelong experience in the reefs of Jamaica, and because I have been directly measuring coral growth rates for years, that I am confident that the mass coral bleaching events of the last 4 years are unprecedented as long as reefs have been systematically studied. We have seen steady deterioration of reefs over the past 40 years, due to hurricanes, overfishing, inadequate sewage treatment, soil erosion, and construction activities, but all of these together have had less impact on reef growth than recent mass bleaching events.

When Caribbean regional mass bleaching began in 1987, many, including myself, found it hard to accept that so severe an impact could be provoked by so small an increase in temperature over that normally found. Since that time we have followed temperature, bleaching, and coral growth rates closely at Discovery Bay. Prolonged exposure to sea water temperatures near or above 30 degrees

centigrade is required for bleaching to take place, and corals can be readily bleached in the lab under these conditions. Because long term regional temperature records were lacking, my colleagues, Raymond Hayes of Howard University, Jennifer Clark of the National Weather Service, Dan Basta, Craig Robertson, and Cathy Woody of the NOAA Ocean Assessment Division, and I have examined the complete record of NOAA high-resolution satellite-derived sea surface temperatures for the Caribbean, compiled twice per week since May 1980. There are only a handful of Caribbean sites where water temperature has been measured directly over this period. Satellite derived temperatures were observed to be a few tenths of a degree lower than values measured in Jamaica. Local reef temperatures depend on the degree of water circulation between each reef and open water, which may be different at each site, so differences between reef and open water temperatures can only be calibrated by long term local measurements. In their absence, satellite data provides a clear picture of regional trends, but may underestimate actual temperatures to which corals are exposed.

Temperatures and bleaching episodes from 1980 to 1990 have been compared for seven locations in the Wider Caribbean: Puerto Rico, Jamaica, Cayman, Cozumel, Florida, the Bahamas, and Bermuda. The relationship of these sites to ocean currents is shown in the first slide. Decadal temperature and bleaching patterns are shown in the next series of figures. Every single case of bleaching reported took place during the highest water temperatures in the record at each site. The 1989 event was most intense in Jamaica and Cayman, which were located in a regional hot spot that year, but bleaching was mild or absent in cooler areas. Bermuda bleached only in 1988, it's hottest year. The spatial and temporal patterns of bleaching are seen to follow the changes in surface temperature. Consequently there can be little doubt that high temperatures are a major prerequisite for bleaching. It appears that temperatures have only begun to exceed the upper tolerance limits of Caribbean corals in the late 1980's.

If temperatures have been unusually high in the late 1980's, can the data be used to determine if regional warming has taken place? We have detrended the data by subtracting the average annual cycle at each site, and examined the trends in the deviation of observed temperatures from their 1980's averages. The next series of slides show clear rising temperatures at Jamaica, Cayman, Florida, the Bahamas, and Bermuda, with nearly half a degree to one degree centigrade increase in mean temperature over the decade. However, no increasing trend is seen at Puerto Rico and Cozumel. We have examined the statistical significance of these trends at each site from May 1980 to May 1990. All increasing trends were statistically significant. We reduced the degree of significance of the data by incorporating a two month temperature memory lag effect into the statistical tests. All trends were still significant except Cayman, which fell just slightly below the cutoff. There therefore appears to be a significant rise in water temperatures at most sites over the 1980's. This was unexpected because we had not anticipated that 10 years would be a long enough record to obtain a statistical trend, due to the magnitude of annual and year to year variability. I have also examined a 10 year temperature data set from Hawaii, where bleaching took place in the late 1980's, and find a similar, and statistically significant, rise. We have measured only Caribbean temperatures, and cannot discuss global warming per se, but we are convinced that regional warming has taken place in the Caribbean, and probably in other tropical reef regions. No physical factor other temperature, and no known pollutant, could cause these patterns. Regional temperature trends could be caused by shifts in winds and ocean currents, as well as by global warming. Corals- are directly affected by high temperatures, whether caused by the greenhouse effect or other factors. We do not now have enough information to distinguish these alternatives.

The statistical analysis requires full-year data sets, and so does not include measurements made since May 1990. Since then, temperatures have risen to record highs and mass bleaching has set in across the Caribbean. Water temperatures this September have been between 31 and 32 degrees centigrade in Jamaica, Cayman, Florida, and the Bahamas, and 32 to 33 degrees in the Central Gulf of Mexico, Cuba, and Haiti. We expect that these unprecedented high and prolonged temperatures, together with cumulative coral starvation caused by bleaching in three of the last four years, will result in many corals dying over the next few months, unlike previous events through which most corals survived despite not growing for up to 10 months.

Like most of my colleagues, I am deeply alarmed at these trends. If they continue, many coral reefs will cease to be viable in coming years. Coral reefs are the tropical rain forests of the oceans, having the highest productivity and most species of any marine ecosystem. They provide crucial, but unquantified, benefits to tropical marine countries through fisheries, tourism, and shore line protection from hurricanes and rising sea level. Until a few years ago, inappropriate local practices were the obvious cause of most reef degradation. Coral reefs now appear to be the first major ecosystem seriously disrupted by climate change, and coral reef countries may become global change's first major victims.

Long term monitoring of bleaching and temperature, research on mechanisms of bleaching, and development of effective techniques for reef restoration and mariculture, based in tropical marine labs, are critical if we are to understand the causes and effects of bleaching, or move towards sustainable management. It is a measure of lack of institutional support for long term research on coral reefs that Caribbean marine labs are still as unequipped and unfunded to do this work as they were when the first mass bleaching broke out in 1987. Local policies to control sewage releases,

erosion, and overfishing, and global ones to halt temperature rise are now essential if reefs are to be saved.

Senator GORE. Thank you very much. Everybody on this panel has done a very thorough job, and I know it has taken a lot of time. This story has not been told to the Congress, and I felt it was worth the time to do it carefully. I appreciate the extra work that all of you have put into organizing this presentation.

Mr. Goreau, you concluded your statement by expressing your personal view. Let me ask you again, do you believe that when all the studies have been done, we will find that the sudden appearance of mass worldwide coral bleaching is primarily caused by increased water temperatures?

Mr. GOREAU. Well, there are a number of physical and chemical factors that can cause bleaching besides warm temperatures; for instance, cold temperatures. But it has not gotten incredibly colder. It has not gotten suddenly much saltier.

None of those other factors are present here. None of them that we are aware of, the things that can cause bleaching in the laboratory, can explain what we see in the field. Pollution cannot, because we are seeing the same phenomenon going on in places that are very distant from human populations, so we do not see another explanation at this point.

For instance, coming back to your question to Dr. Earle, in fact there was no known pollutant whose pattern could explain this.

Senator GORE. Do any of you doubt what the ultimate conclusion will be on this? Do all of you have a gut feeling, or a personal opinion, that the coral bleaching events worldwide are related to the elevated temperatures of the waters in which these reefs live?

Mr. Williams, do you agree with that, personally?

Dr. WILLIAMS. Yes.

Both the experimental and the large-scale information agree with that.

Senator GORE. Mr. Wicklund?

Mr WICKLUND. Yes, sir, I think temperature is the cause, but we need more data.

Senator GORE. Mr. Jaap?

Mr. JAAP. Yes, Senator.

Senator GORE. Mr. Hayes?

Mr. HAYES. Very much so, Senator.

Senator GORE. Well, it is very significant. It is startling and very disturbing news. Do you, Dr. Hayes, have specific recommendations as to what needs to be done on the research agenda, and keep the response brief, if you could. We are going to have NOAA in the panel after this global temperature panel coming next.

Mr. HAYES. Yes, Senator. We have introduced into the written testimony a five-point proposal that we believe might begin to resolve this problem. I will just go through it very briefly.

First, we believe that there is a definite need to deploy long-term regional monitoring stations throughout the Caribbean Sea in order to collect the descriptive data that is necessary to document the changes occurring there.

Secondly, we believe that there is an urgent need to have a research conference of scientific investigators both from the United States as well as from Caribbean nations in order to summarize our most comprehensive understanding and develop a strategy for proceeding.

Third, we believe that there is a need to prioritize a significant pool of funding for investigator-initiated research programs, including the type of program that Dr. Williams referred to as a rapid response deployment.

Fourth, we believe that there is a need to establish a network to both receive and disseminate information concerning local events that are occurring throughout the marine environment. Only by having this information will the mass media be properly informed, public agencies as well as individual scientists will have the information that they need.

Last, we believe that it is necessary to extend remote sensing activities predominantly through NOAA into the Caribbean area so that we have the broad-based satellite data that I believe has some validity in this particular scientific approach.

Senator GORE. Well, very good.

I have some questions that have to do with your difficulty in getting access to the NOAA satellite data just because of the form in which it is collected and compiled, and the inadequacy of the research agenda that is being pursued.

I want to explore those fully, and I hope that the five of you can remain available until the end of the hearing. I would like to get you together with some of the NOAA folks afterwards, and I would like you to hear their testimony on the third panel.

In the interest of time we are going to move to the panel on global temperatures.

Thank you very much, Dr. Goreau, Dr. Williams, Dr. Wicklund, Mr. Jaap, and Dr. Hayes. Thank you. We will be talking further with you.

I would like to call our second panel now. Roy Spencer of the Marshall Space Flight Center in Huntsville, Alabama, accompanied by John Christie from the Johnson Research Center at the University of Alabama in Huntsville, and Philip Jones, Climatologist, at the University of East Anglia in Norwich, England. Please proceed to the witness table.

Let me say in introducing this panel that Philip Jones, together with Tom Wigley, has collected, analyzed, and corrected for errors, every available historical land-based and sea-based temperature record, and has gone through painstaking efforts to correct and compensate for the type of measurement, including examining the materials the buckets were made of that were dipped down to get the samples from the ocean. He will present some brand-new data from 1990, and we are looking forward to that.

Our witnesses from Huntsville have compiled a rather extraordinary new way to measure global temperatures. As I indicated, their report in "Science Magazine" earlier this year was misinterpreted by some, and we will talk about that as well. We want to start with Philip Jones. I want to welcome you, thank you for the great distance you have traveled, and, I invite you to proceed.

## STATEMENT OF PHILIP D. JONES, CLIMATOLOGIST, UNIVERSITY OF EAST ANGLIA, NORWICH, ENGLAND

Mr. JONES. Thank you. Thank you for inviting me to come over and give this testimony. I want to just briefly summarize the work that we've been doing over the last 10 years.

We have collected over the last 10 or 12 years about 3,000 time series of temperature records from the land areas of the world. Before we began analyzing these, we had to make sure that each of the individual time series was indicative of past temperature variations.

We had to weed out stations which were what we called nonhomogeneous whose trends are not always related to the climate. Many of these nonhomogeneous site records come from numbers of different sites within a small area, and so there are problems caused by site changes. The instruments change as new ones are developed through time. Observing practices change,

and there may also be problems related to the growth of the site or the growth of the city around a particular site—the urban warming effect.

This whole process took about 5 person years of effort checking all of these stations, making comparisons, and deciding which stations were good, which stations were bad, and which ones we could correct.

[Slides shown]

The plot on the figure shows the time series for the Northern Hemisphere, Southern Hemisphere, and the globe in the three frames.

The x-axis is time along the bottom from the middle of the last century up to 1990, and the y-axis is the temperature scale in degrees Celsius, anomalies or departures from the 1951 to 1970 average. The individual years are plotted as the histogram, and the smooth curve is a 10-year average fit through the individual yearly values.

Senator GORE. Now the top one is Northern Hemisphere?

Mr. JONES. The top one is Northern Hemisphere.

Senator GORE. The middle one is Southern Hemisphere and the bottom one is global?

Mr. JONES. The global is the average of the two hemispheres, yes.

Senator GORE. And it goes from 1854——

Mr. JONES. This is based only on land data. I was coming back to the marine curve in a minute. This one is not in the sheets I gave you.

Senator GORE. Go ahead.

Mr. JONES. You can see that the Northern Hemisphere, because it has a much greater land area than the Southern Hemisphere, varies more from year to year. You can see that overall temperatures during the 1980's are about half a degree Celsius warmer than they were during the 19th century in both hemispheres.

The warming is much more gradual in the Southern Hemisphere, somewhat erratic in the Northern Hemisphere, where we see warming up to about 1940, cooling till about the late 1960's, 1970 period, and warming since then.

This is for the land areas. This is only about 30 percent of the surface area of the Earth. In order to get a true global record, we need to incorporate the ocean areas as well. In doing this, we have taken data on sea-surface temperature readings which have been compiled into a big data set by scientists at NOAA and NCAR. It is called the Comprehensive Ocean Atmosphere Data Set.

Now marine data are also subject to problems of homogeneity through time, as with the land record. The basic problem with marine data is that in the 19th century, the ships that took the readings were often sailing ships and they used fairly primitive ways of sampling the sea water. They would throw a bucket over the side. It may have been a wooden bucket, a tin bucket, and towards the end of the century it was a canvas bucket. They used to haul some sea water on to the deck and measure the temperature.

This method has become an antiquated way of doing things with modern shipping fleets. And now, most readings are taken using the water that is taken onboard ship to cool the engines. The temperature is measured in these cooling water intake pipes. We believe that this process began sometime during World War II. So most of the readings since World War II are these engine intake readings. Most of the readings prior to World War II are made with these buckets. And we developed a technique of correcting the earlier bucket readings in collaboration with the people at the Meteorological Office in Britain, and we were able, then to correct each reading for each individual square of the ocean. This is on a 5-degree latitude by 5-degree longitude grid.

We were then able to incorporate the marine areas of the world which are about 70 percent of the earth's surface, with the land records, and produce what

we believe is the best possible global coverage for the two hemispheres and for the globe.

There are obviously problems in the last century, and even in the early parts of this century, with poor coverage, in some parts. So in the 19th century the coverage in the Northern Hemisphere is not very good in parts of the tropics and in parts of the Pacific Ocean, and the coverage in the Southern Hemisphere is not very good even now over parts of the southern oceans.

Antarctic data came in 1957, and so we have a gradually changing coverage through out the period of record. In order to assess that changing coverage does not bias our results, we have with a series of tests compared what the coverage of the 19th century would do to records during the period from 1950 onwards. Using the coverage that was available then, we have derived hemispheric averages and compared these with what we would get with the full coverage now. It seems as though the earlier coverage does not bias the results too much.

We think that the year-to-year values we get for the Northern Hemisphere are valid about to 1875. And for the Southern Hemisphere, they are reliable back to about 1890.

As you can see on this plot, the 1980's are clearly the warmest decade. And I want to look now in more detail at the special pattern of change during this particular decade.

This is a plot of the whole Northern Hemisphere. It's an anglocentric view of the world—Britain is in the middle at the bottom there, and North America is off to the left. The map looks down at the North Pole. The Pacific is at the top, Africa is at the bottom, and Asia is on the right.

And this plot shows contours of the average temperature during the 1980's. This is 1980 to 1989, compared to the previous three decades, 1950 to 1979. And you can see that the areas which show the greatest warming are over Eurasia, particularly over the Soviet Union and parts of Northern Siberia are up to 1 degree Celsius warmer—the whole 10 years has been 1 degree Celsius warmer than the previous 3 decades.

Senator GORE. And what is that Fahrenheit?

Mr. JONES. You multiply these numbers by 1.8, so it is 1.8 degrees Fahrenheit warmer than the 30-year average. Temperatures are also 1 degree Celsius warmer over parts of the Canadian prairies. And you can see this area of warmth during the 1980's stretching down from Alaska towards the American Midwest.

You also see warmth over West Africa and parts of the tropical oceans. But you see that even during the 1980's, which are clearly the warmest decade, that temperatures were over half a degree Celsius cooler than the previous 30 years over parts of the North Pacific stretching from Japan across towards Hawaii, and in the North Atlantic region, particularly around Greenland and parts of Eastern Canada. The comparable one for the Southern Hemisphere.

I would again point out there is a lack of data even now over the southern oceans south of Australia and South Africa toward Antarctica. It is very poor coverage, now. This may improve from the late 1970's onwards as a result of satellite data, but from ship-based data, we are not going to be able to improve the record prior to 1980.

As you can see on this map, the 1980's were warmer than the previous 30 years over almost the entire hemisphere. There are just three areas which were cooler, two small areas over Antarctica, and a part of the Amazon basin in South America. Temperatures were up to half a degree Celsius warmer over large parts of the tropical East Pacific, parts of southern South America, Antarctic Peninsula, southern Africa, and some parts of eastern Antarctica.

That is one way of looking at the 1980's. Another way is to look at the trend of temperature over the last 20 years. Now I will show you the one for the Southern Hemisphere first since I cannot find the Northern Hemisphere one.

This now compares essentially—compares the 1980's with the 1970's. How much was the present decade, or the decade that just finished, compared to the decade before you can see that temperatures over the last 20 years have warmed by on the order of a degree Celsius over parts of the eastern tropical Pacific, over parts of southern Africa, and parts of the Indian Ocean.

And you may recognize the strong warming over parts of Australia, which may explain why Australian politicians are very interested in the greenhouse effect because they can actually see the warming going on in their particular area.

Senator GORE. And in terms of the last panel, that could explain the event at the Great Barrier Reef, as well.

Mr. JONES. It could possibly, yes. Although temperatures off the coast of eastern Australia seem to have changed little.

I cannot seem to find the corresponding one for the Northern Hemisphere, but it shows a similar pattern to the 1980's. And you can see there has been strong warming again in parts of the USSR, western North America, and in parts of North Africa and coming around towards the Indian subcontinent, and Southeast Asia.

I want to now go on to the very recent few months and show three more slides.

The first shows the monthly temperature anomalies for the 1980's and the first 8 months of 1990. Now again, these are in histogram form for the individual months and the smooth curves are sort of a running annual average.

For the Northern Hemisphere you can see that temperatures are generally above the zero line throughout the decade and the zero line being the 1951 to 1970 average. This is for the land areas only.

But overall, if you just ignore the last values for 1990, there is no overall trend, either in the Northern Hemisphere or the Southern Hemisphere. Temperatures are, just on average, about 0.2 or 0.25 degrees Celsius above the zero line.

Senator GORE. Now that is during the 1980's?

Mr. JONES. During the 1980's, yes. But if you come up to the last few points on the top curve, you can see that the very anomalous conditions that have occurred during the late winter and early spring in the Northern Hemisphere over the land areas. And the major anomaly is during March this year, when temperatures over the land areas in the Northern Hemisphere were 2.2 Celsius warmer than their 1951 to 1970 average. And this is an amazing anomaly.

Senator GORE. Could somebody multiply 2.2 times 1.8?

Mr. JONES. You're going to get about 4, I think.

Senator GORE. So what you're saying is that during the first months of 1990 over the land areas of the Northern Hemisphere, the temperatures were roughly 4 degrees Fahrenheit higher than the average over the previous few decades.

Mr. JONES. Just during March. Obviously for January and February and April, the temperatures were nearer to normal, but still on the order of 1 degree Celsius above the previous decades, yes.

Senator GORE. And these are corrected for the annual seasonal fluctuations?

Mr. JONES. Yes. So these take away from each station its normal annual cycle of temperatures.

Senator GORE. Four degrees warmer than the average March temperatures for the last how many years?

Mr. JONES. This is for the period 1951 to 1970.

Senator GORE. Since 1951.

Mr. JONES. Now these were for the land areas. Including the marine areas and because the marine areas do not fluctuate so much from month to month and from year to year, this tends to damp out the month-to-month oscillations in the land record. You still see the very anomalous conditions in March of this year, temperatures now, when combining with the marine data, are 1.2 degrees Celsius above the 1950 to 1979 average.

And you can also see the temperatures in the Southern Hemisphere here are at this sort of constant level of about 0.3 degrees Celsius above the value for the previous 3 decades.

And again, you cannot see any sort of trend over the period of the 1980's. There are warm years at the beginning in the Northern Hemisphere, some cool years in the middle, and some warm years again at the end. And the Southern Hemisphere just has fairly sort of conditions at about the 0.2 to 0.3 degrees Celsius level throughout the decade.

Senator GORE. So if you just look at the 10 years of the 1980's, you do not see a trend during that 10-year period, but the decade as a whole is significantly warmer than the prior 2 or 3 decades.

Mr. JONES. Yes, the decade as a whole is 0.2 degrees Celsius above any other decade. So it is clearly, without doubt, the warmest decade that we have recorded since comparable records began during the middle of the last century.

Just finishing the point about March this year. This is a map for the Northern Hemisphere, and you can see now contours of the average temperatures with respect to the previous 30 years. Over the Soviet Union, particularly over northern Siberia, temperatures there during March were up to 10 degrees Celsius warmer than the average March conditions.

And so, for example, at Verchojansk, which is in the center of that area, instead of being about minus 20 Celsius, it was minus 10 Celsius.

Senator GORE. I was able to do that multiplication in my head. That is 18 degrees Fahrenheit warmer in Siberia than the average March?

Mr. JONES. Yes.

Senator GORE. Eighteen degrees Fahrenheit?

Mr. JONES. Yes. I was pretty alarmed by these values and spent the best part of a couple of days checking it that all the numbers were correct. You can do comparisons between stations, plot out the data and make sure that you don't have any erroneous data points going into the analysis.

You can also see that temperatures were also warmer over most of North America, particularly over the northwestern parts of Canada, where temperatures were up to 6 degrees Celsius warmer than normal. And temperatures were also enormously warm over parts of West Africa. But even during this period, which was quite clearly the most anomalously warm month we have ever recorded, temperatures were up to 4 degrees Celsius colder over parts of southern Greenland and the neighboring areas of eastern Canada, and colder than normal over parts of northeast Africa.

The final one just shows the same type of map for the Southern Hemisphere. It shows the conditions there were much nearer to the normal with anomalies only on the order of 2 degrees warmer and 2 degrees colder than normal. Overall that averages out at about .3 degrees Celsius warmer than the average, nothing like the 1.2 degrees we see in the northern hemisphere.

The upshot of this is that it is, because the marine data take a long time to warm up and cool down, 1990 should be, unless we have a very cold end to the year in December and November, in the northern hemisphere, the warmest year. I made an extrapolation at the beginning, and I would just put this one back up again.

You can see the final point on the curve, on the plot, is the 1990 value, which includes data for the first 8 months of the year, i.e., through August, and then includes the average values for September to December that have occurred during the 1980's, and that is probably a fairly conservative estimate, because I am aware that temperatures have been fairly warm during September and the first part of October in many parts of the world.

Senator GORE. It seems a little warm here the last couple of days.

Mr. JONES. It is exceptionally warm here.

Senator GORE. What you are saying is that even though there are 4 months of the year 1990 not included yet in your data, the first 8 months of the year have such extraordinarily high temperatures worldwide that you already can make the statement that 1990 will almost certainly be the hottest year in recorded history.

Mr. JONES. Yes, I can be fairly confident on that, simply because of the fact that we include ocean data, and the oceans will not cool down very quickly over the next few months. But really, the March value is the key to making this year the most anomalously warm.

[The charts referred to follow:]

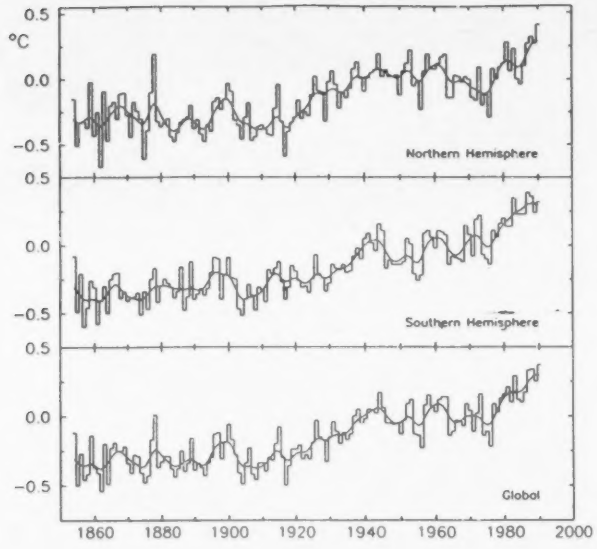



Figure 1: Annual hemispheric and global temperature averages, 1854 to 1990. Data are expressed as departures from the 1950-1979 average. The smooth curve is 10-year Gaussian filter designed to highlight variations on decadal timescales. The 1990 value is a provisional estimate based on data for the first eight months of the year.

Figure 2: Spatial pattern of average annual temperatures during the 1980s. The data are expressed as departures from the 1950-1979 average.

Figure 2: Spatial pattern of average annual temperatures during the 1980s. The data are expressed as departures from the 1950-1979 average.

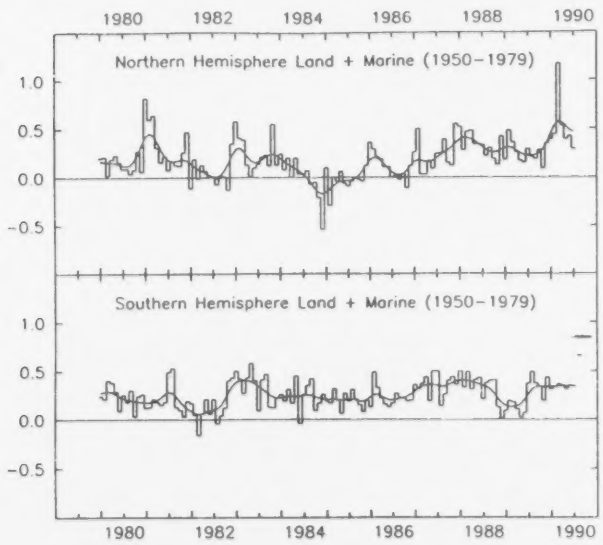



Figure 3: Monthly hemispheric temperatures, 1980 to 1990. Data are expressed as departures from the 1950-1979 average.

Figure 4: Spatial pattern of temperature departure, during March 1990 over the Northern Hemisphere. Data are expressed as departures from the 1950-1979 average.

Senator GORE. Have you concluded your statement?

Mr. JONES. Yes.

Senator GORE. Thank you very much. I appreciate your testimony, and I am going to hold my questions until we have heard from the next panel.

Let me say that in our third panel we will have Dr. Knauss and this morning we have received some rather troubling documents about the preparations for the second world climate conference, and I will be asking Dr. Knauss, who is leading our team there, about our response as a country to this worldwide effort to deal with the consequences of what the scientists are telling us this morning. It appears from these documents that the U.S. team is attempting to sabotage the second world climate conference, but we will get into that in the next panel.

I want to give a special welcome to the two scientists from Huntsville, Roy Spencer, who is accompanied by John Christie. I personally found your new methodology to be extremely exciting and valuable, and I want to congratulate you, and through you, your team, for the imaginative work that went into this whole study. We welcome your statement.

If you could compress it somewhat I would appreciate that. You are most welcome. Please

**STATEMENT OF DR. ROY SPENCER, MARSHALL SPACE FLIGHT CENTER, HUNTSVILLE, AL; ACCOMPANIED BY JOHN CHRISTY, JOHNSON RESEARCH CENTER, UNIVERSITY OF ALABAMA**

Dr. SPENCER. Thank you, Mr. Chairman. We certainly appreciate this opportunity to present to you some results from the satellite temperature measurements, and also, hopefully, to set the record straight, as you had mentioned in your original introductory remarks that some of the media attention we got did in fact misrepresent what we were saying.

By way of introduction, I would like to mention that we are going to deviate a little bit from our written testimony, because, based upon what we have heard in the previous panel about coral bleaching, which we knew nothing about 2 days ago and now which we know a little more about, I have to admit that we saw some remarkable correlations between what they were saying in their corals and what we were seeing in the global temperature record.

Mr. Chairman, earth-orbiting satellites are now providing some really exciting data for doing climate studies. Microwave radiometers that have been flying on NOAA satellites since 1979 have been providing continuous global temperature measurements, but over very deep layers of the atmosphere.

We have determined from satellite to satellite inter- comparisons during this period—because usually there are two satellites operating—we have determined that these satellites can monitor these deep layer air temperature measurements, or their variability on a month-to-month basis, to a 1/100th degree precision, which was very exciting to us.

Furthermore, and probably at least as important to the global warming issue, is the capability that we have found in these satellites to monitor any long-term trends. That is, let us say, decadal time scales. We found through comparisons to hundreds of thousands of weather balloons that there is no net trend—when we compare the weather balloon data to the satellite data, there is no net trend in their difference, and what this means is, to our ability to determine it statistically, there is basically no drift in the satellite system on a global basis.

Dr. SPENCER. I am going to show a global summary of what our global temperature trends look like since the record started in 1979, and probably the most important thing to point out—now, this is globally averaged, and you see the time scale on the bottom. We are going from 1979 through just about the end of 1989, which is as far as we have data.

I think the most striking thing you find in terms of the globally deep layer averaged air temperatures is that there is tremendous variability from year to year, and in fact I think the coral researchers from the previous panel will recognize the main bleaching events are related to these big El Niño events, especially 1983 and 1987, but certainly the most important thing to point out here is the large year-to-year variability.

Now, over this near 11-year period we find that there is essentially no net trend up or down.

Senator GORE. Let me interrupt you there to say that the previous panel specifically examined mass bleaching events that occurred in non-El Niño years.

Dr. SPENCER. That is right, and I am going to address the temperature anomalies for that specific portion of the world in a minute.

Now, as I just mentioned, there is no net trend over this 11-year period of time, but I want to make it very clear that that is really quite meaningless in the sense that because the variability from year to year can be so large, it can very easily mask out any long-term trends, which means it just takes a longer period of record before you can determine any slight upward trend, let us say, due to global warming, in the presence of all this natural variability.

That is probably the point that we were misrepresented on by the media, as we said that there was no net warming trend during the 10-year period, and now this is 11 years, but really that is quite meaningless, and in fact, if Phil Jones is correct that 1990, which is not on this graph, is the warmest year yet, then of course our 12 years then through 1990 will have a net upward trend, that is for sure.

Now we had to pull out a couple of viewgraphs because of the testimony of the coral people. The upper graph is the same one that I just showed. The bottom graph shows the distribution of where these warm anomalies were, in terms of earth latitude band. Here is the equator running through here—North Pole, South Pole.

What I want to point out here is that during 1983 this big warm event right here was concentrated in this latitude band, plus or minus 30 degrees, okay? The tropical belt is right through here. This is basically latitude versus time, okay, and this was a big warm event in 1983 which occurred in the tropics.

Now, we see back in 1980 there was also a slight warm event, and as we heard previously, there was a coral bleaching event associated with that, and in 1987 there was a big warm event. Now, as the previous panel pointed out, this was supposedly the strongest ENSO event ever on record, 1983, and in fact we find that in the Pacific, where people generally talk about the ENSO occurring, it was——

Senator GORE. Now, ENSO is another way of saying the El Nino?

Dr. SPENCER. The El Niño southern observation. It was very strong in there, but we were very surprised in 1987 that even though it was not as strong in the Pacific, the 1987 ENSO phenomena spread its warmth throughout the tropics, so that globally averaged the tropics were even warmer during this period of time than they were in this period of time.

Now, at this point, I want to make a clarification. Dr. Goreau, that previously showed some satellite data, the data—the sea surface data he was showing from the AVHAR instrument on the same satellite that this instrument is from said that they did not pick up a warm sea surface temperature anomaly in 1983.

I want to point out that the people that work with those data realize that in 1983 we had this El Chichon eruption down in Mexico which put a lot of dust in the stratosphere and during 1983 it was basically impossible to get good sea surface temperatures in the tropics, and that is why they did not get very good agreement between the satellite and the surface.

But continuing on here, I just want to reiterate that there were warm events in the tropics corresponding to those bleaching events.

Senator GORE. This is brand-new. The coral scientists have not really seen this data yet.

Dr. SPENCER. No. I would suspect they would be interested in looking at these.

Senator GORE. I would suspect they would. What you are saying is that after listening to the coral scientists testify, you went back and looked at some of the details of your measurements by latitude and found an even more exact correlation——

Dr. SPENCER. That is right.

Senator GORE. ——between temperature globally and the appearance of coral bleaching globally. All right, go ahead.

Dr. SPENCER. Okay. This is the 1983 ENSO event. This just shows the locations of warm and cold anomalously warm and cold air masses. This in particular is early 1983, and we see this tremendous warming out over the Pacific, and of course there was tremendous coral bleaching events out there during that period of time.

But during 1987, during that El Niño event, this was not nearly as strong, but the warmth spread all the way across through the global tropics, so that while the Pacific El Niño was not as strong, per se, the warming in the whole tropical bands was in fact warmer than in 1983, and I think they will be very interested in knowing that.

Now, I agree with Phil Jones that even though we really do not see any trend during the 1980's, there is considerable evidence, in addition to his surface phenomena data, that the 1980's were unusually warm. We found that we have got a nearly perfect correlation between the satellite data and the globally averaged weather balloon data, where there are weather balloon observations made, and on this chart these lines indicate yearly temperature anomalies from the weather balloon data since the late 1950's.

Now, this extends up through 1988. The dots are satellite yearly globally averaged temperature anomalies, and we find that if the dots end up on the end of the lines, that means there is a perfect correspondence. We find there is very good correspondence. In fact we just, on the way here, figured out our 1989 dot from the satellite, and it will be right at the end of this line.

Basically, what I am saying is that there is very good agreement between our satellite data and the weather balloon data, and if you look back in time, the weather balloon data do say the 1980's were indeed warmer, as a decade, than the 1960's or the 1970's.

Senator GORE. All right, let me stop you right there.

Your work is extremely significant, because you have created a new and more accurate way to measure global temperatures. You can now measure global temperatures very precisely, but the satellite you use to get your temperatures only started giving you data 10-12 years ago?

Dr. SPENCER. That is right.

Senator GORE. Your study only covers the last 10 years?

Dr. SPENCER. That is right.

Senator GORE. But now, you are able to correlate your measurements from this new precise method with the measurements that Phil Jones and his colleagues have made using detective work and balloon observations. You find that the 10 years you are able to measure, correlate very closely with the way Jones measured temperatures, correct?

Dr. SPENCER. On a year-to-year basis, yes. We see that the inter-annual variability—the bumps on the curve—year to year match up very well. We were a little surprised about that. We thought a lot of that bumpiness might be due to noise, due to the fact that the earth is not covered with thermometers, but in fact they do correlate quite well.

Now, in terms of long-term trends——

Senator GORE. Now, wait a second. Let me stop you there.

Dr. SPENCER. Okay.

Senator GORE. Since they correlate so well during the 10 years that you have been measuring these temperatures, do you think it is fair to conclude that Jones'

measurements for prior decades, where you do not have temperatures, are probably pretty good, too?

Dr. SPENCER. They correlate well for the yearly variability, and therefore I think that the yearly variability in previous decades is probably good and is probably real in the thermometer data, but the yearly variability is different for long-term trends. Basically with our satellite data we cannot say anything about the quality of the surface record in terms of any long-term trend since the late 1800's. I do not think it can be used in that fashion.

Senator GORE. That is where you were misinterpreted. You said, "We have got this exciting new way to measure temperatures with much greater precision." It is in fact a fantastic accomplishment. Further, you said, "what do we see during 10 years?" Well, we saw some hot years at the beginning of the 1980's, and then it cooled off a little bit. Later, it warmed up a little bit, but statistically we do not see a long-term trend reflected during the 1980's.

Some people took that and said, "aha, no global warming." "Science Magazine" in particular, put out a press release hyping the forthcoming publication of your study, and in the process severely distorting what you were saying. At least, that is the way I read it. Of course they got more attention to the magazine by saying we have got a new, scientific study that shows there is no global warming, but it was really, in my opinion, irresponsible to hype it that way.

But one of the things your study does show is that Phil Jones' data for the 1980's are pretty good. That means that insofar as you can testify to it, his data for the 1970's and 1960's are probably pretty good, too. Since that is a three-decade period instead of a one-decade period, the trend which Phil Jones shows is probably supported by the data that you have for the final decade of that three-decade period.

Dr. SPENCER. Well, I agree basically, and of course, this is a third data set—the weather balloon data—and since the weather balloon data do agree with the surface data that the 1980's were warmer than the previous two decades, I think that I am convinced beyond any reasonable doubt of that. Certainly, our satellite data I do not think show anything that would cast doubt on the last 100 years of global surface data.

Senator GORE. Further, you say if you take the temperatures for 1990, which Phil Jones has just told us will almost certainly be the hottest year ever, and if your measurements continue to roughly correlate with what he is finding, then you take not a 10-year period but an 11- and 12-year period, which you will be able to say with your new satellite data, there is a statistically significant warming trend over that 12-year period.

Dr. SPENCER. If, indeed, the satellite data basically show the same thing that Phil was saying with the surface data, I suspect there will be a statistically significant upward trend for those 12 years.

Senator GORE. Well, of course, all of this will have less impact on the policy of the Bush administration than John Sununu's personal computer.

Because that is what is setting policy, as far as I can tell. But I really think that it is significant, what you are telling us here today. Now, I interrupted you, do you have some more to tell us?

Dr. SPENCER. No, nothing, nothing that impacts the coral issue. Just to point out that this is the only global data set we are going to have now and in the future. I think it is going to be very valuable for many studies, not only for monitoring but validating climate models, and we thank you very much for the opportunity to review our work for you.

[The statement follows:]

## STATEMENT OF DR. ROY SPENCER, GEORGE C. MARSHALL SPACE FLIGHT CENTER, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Mr. Chairman and Members of the Subcommittee: I am very pleased to have the opportunity to appear before the Committee to discuss recent research regarding the nature of global temperature measurements and their importance.

Mr. Chairman, in the last few years earth orbiting satellites have begun to provide new and exciting information concerning the Earth's climate. NASA satellite programs planned for the coming years, including the Earth Observing System (EOS), promise to revolutionize our understanding of the Earth and to enable scientists to design models that will predict the future state of our planet.

In the context of global air temperature measurements, I would like to address the following four major issues:

1. The Validity of Satellite Atmospheric Temperature Measurements for Climate Monitoring 2. What the Current Satellite Data Reveal 3. The Relationships between Surface, Atmospheric (Balloon), and Satellite Temperature Measurements 4. The Future Impact of Satellite Monitoring on Climate Prediction

### THE VALIDITY OF SATELLITE ATMOSPHERIC TEMPERATURE MEASUREMENTS FOR CLIMATE MONITORING

Microwave radiometers, built by NASA and flown by the National Oceanic and Atmospheric Administration (NOAA) since 1979 on the TIROS-N series of satellites, have revealed a remarkable capability to precisely monitor globally-averaged monthly atmospheric temperature variations. Monthly readings over relatively deep layers (1-10 kilometers) of the atmosphere from concurrently-operating satellites during this ten year period have consistently been within 0.01 degrees Celsius of each other. These microwave observations are nearly unaffected by the presence of intervening clouds, and the manner in which the instruments are calibrated ensures long-term stability of their measurements. It is important to note that global warming caused by an enhanced greenhouse effect would manifest itself by an increase in deep-layer atmospheric temperature.

Comparisons of these satellite measurements with hundreds of thousands of weather balloon measurements also show good agreement between readings over specific locations. The comparisons (results not yet published) were performed for specific weather balloon locations across the contiguous United States, Alaska, the Caribbean, and the Pacific. Atmospheric balloon readings at these locations were compared with satellite observations over the same locations to detect differences in the readings themselves. The two methods show very strong agreement in monthly atmospheric temperature anomalies observed at these specific locations, and many individual locations showed a nearly perfect match between the balloon and satellite observations in measuring annual temperature shifts. The methods also agree for regional trends on decadal time scales.

I believe the consistency of readings between the individual satellites, and between the satellites and specific balloon measurements, validates the use of satellite measurements to monitor small atmospheric temperature changes on decadal time scales over the entire globe.

### WHAT THE CURRENT SATELLITE DATA REVEAL

The satellite data for the last eleven years reveal a large year-to-year variability in globally-averaged atmospheric temperatures (Figure 1). The satellites show only a small (0.03 degree Celsius) downward trend in globally-averaged temperatures for the period from 1979-1989. However, the large annual variability of the readings makes it problematic to interpret a quantifiable trend, especially since the addition of a single warm or cold year to the data set could alter the overall direction and magnitude of the change. This is especially true when smaller regions are addressed, because year- to-year variability in these regions can be even more pronounced.

### THE RELATIONSHIPS BETWEEN SURFACE, ATMOSPHERIC (BALLOON), AND SATELLITE MEASUREMENTS

The globally-averaged satellite data findings discussed above generally agree with global averages from balloon and surface thermometer measurements during the same period. All three measurement systems show significant year-to-year variability in globally-averaged temperature readings.

Agreement was strongest between the balloon and satellite data. As with the TIROS-N satellites, balloon instruments measure the temperature of the lower atmosphere in the same column of air. As noted earlier, the similarity of readings establishes a strong link between these two measurement systems, and makes it reasonable to expect that satellite observations can be used to measure the atmospheric temperature of areas where no balloon observations are possible.

There was a small difference (0.1 degree Celsius) between the ten year trend of the satellite data and surface-based temperature readings between 1979 and 1988. Surface measurements reflect

temperature readings in the thin envelope of air within a few meters of the ground. I believe the difference between the satellite and surface measurements may very well reflect a real difference between surface and deep layer atmospheric temperatures, rather than indicating any flaw or bias in the surface data. While there is a clear correlation between surface and atmospheric temperatures, it is reasonable to expect differences in measured readings and in annual changes. Moreover, it is possible that surface readings from locations outside the North America may not have yet been adequately corrected for the effects on temperature of increased regional urbanization. For these reasons, I do not believe that the findings of our atmospheric satellite measurements study (Science, March 30, 1990) can be used to cast doubt on or confirm any surface thermometer measurement trends before 1979.

Despite the year-to-year variability in temperature indicated by satellite, balloon, and surface-based systems, the balloon and surface measurement systems show that the 198~'s were warmer than preceding two decades. Examining the balloon and satellite data over the last 30 years, Figure 2 indicates a net warming trend during that period.

## THE FUTURE IMPACT OF SATELLITE MONITORING ON CLIMATE PREDICTION

Despite the public perception that historical temperature trends can be used as a means for predicting future changes, improved measurements of global temperature by satellites are critical to global change research. Satellite observations offer a significant opportunity to expand our database on atmospheric temperature trends. The impact of these satellite measurements in the global warming debate is concentrated in two major areas.

First, satellite measurements offer the only means of acquiring a long-term, high precision, global data set for atmospheric temperature measurements for detecting enhanced greenhouse warming. Combined with balloon and surface-based measurements, satellite data offer the promise of an increased understanding of global temperature trends and patterns.

In addition, as this data set expands during the next decade into the EOS era, we will be able to improve the accuracy and completeness of global climate models. Satellite data will be essential to validate these computer climate model simulations, especially in remote regions of the Earth that are not well sampled by surface thermometers or weather balloons. Having such data will allow researchers to compare the results of their predictions with actual data and to focus on those aspects of the model which are problematic.

This validation potential can be exploited immediately and should improve the way these models treat complex interactions between the oceans, atmosphere, clouds, radiation, etc. As we improve these models, we will enhance our confidence in predicting global temperature changes for the future and in understanding the nature of global change.

Thank you, very much.

Senator GORE. Well, thank you, and let me say again, I am extremely impressed with what you all have done in Huntsville. This means that in the future, there will not be as much guesswork from year to year. You have discovered a very precise measurement.

What is the time lag in the reporting of your data? How long does it take you to get it all? For example, March 1990, which is so completely off the charts in Phil Jones' measurements, how long before we have your data on March of 1990?

Dr. SPENCER. Well, we have been working that problem, I should say my managers have been working that problem for quite a while now. Gee, if we would have known that 1990 was going to be off the scale, maybe we would have worked harder to get the data sooner.

We are hoping early next year to have continuous, data continuously coming in electronically on a daily basis so that we would basically have daily updates.

Senator GORE. On a global basis?

Dr. SPENCER. On a global basis. But as of right now, we are still waiting to get the last, basically the last year's worth of data.

Senator GORE. Is that budget sensitive? That is a dangerous question to ask any——

Dr. SPENCER. Yeah, probably dangerous for me to answer, too.

Senator GORE. Let me give you a clue. The answer is yes.

Dr. SPENCER. If there was more money available, either for us, NASA, or NOAA, it would have been done before now.

Senator GORE. I would like to ask the staff of the committee to follow up with you all on a more detailed answer to exactly how we can get this data more quickly, but now you are telling us we will get the 1990 data probably early next year, the first part of 1990.

Dr. SPENCER. Or sooner. In all honesty, there has been still a lot of researchers that are not quite sure what we have done, so that there is not necessarily support throughout agencies like NOAA and NASA for what we have done. There is a lot of good support and there is some skepticism because our claims are, of precision are so great.

Senator GORE. One-one-hundredth of a degree.

Dr. SPENCER. Yes, well, we still do not believe it, so that there is probably a little bit of that problem, too, you know, should we really act quickly on something we are not even sure is really a good, as good as they say it is.

Senator GORE. It is sort of like the problem that surgeons now face with their magnetic resonance devices. They get more information than they can understand, and they are a little scared to use it. But I think what you have done is really terrific, and I would like to work with you in getting wider use of the data that you have compiled.

Dr. SPENCER. Well, thank you very much, Mr. Chairman.

Senator GORE. We refer to Huntsville as southern Tennessee, anyway.

We are running overtime, and Dr. Knauss has arrived. We will ask our third panel to come forward. Before we close here, again Dr. Jones, did you want to add anything to what you have said previously?

Dr. JONES. Just one small point on the last discussion.

Senator GORE. Yes, please.

Dr. JONES. The satellite data are telling you something about the temperatures in the lower and middle atmosphere, and my data is telling us what is happening at the surface. So the two are not necessarily the same, and everyone lives at the surface, so I do not want you to go away with the impression that the satellites are a replacement for the surface network. We really need the surface network, we need that to be continued in its present state.

Senator GORE. Well, I was lavishing so much praise on this Huntsville team that I might have inadvertently given you that impression, but that is not my feeling at all.

Dr. SPENCER. John and I would like to go on record as fully supporting what Phil said. We agree.

Senator GORE. Well, thank you for that clarification, and a very important one indeed. And thank you for making the trip from East Anglia, too. The observations about 1990 are particularly alarming, especially the observations about March. Some of the figures in Siberia and elsewhere appear really incredible. You said they seemed incredible to you also. That is why you went back to double-check and triple-check your data, but it is actually happening.

Dr. JONES. Yes.

Senator GORE. All right, well, thank you very much. We are going to go to our third panel now. Dr. Knauss, would you prefer to appear as an individual witness? Well, why don't you come on up and we will ask the others to join you. We will take you first and then turn to the others.

I know that you have got a busy agenda today, and I want to get you in and out as expeditiously as possible. If the others could join you up here, they may help you answer some of the questions about the agency's response to the coral bleaching panel and the temperature panel.

Dr. KNAUSS. Yes, if I could bring Dr. Wildman with me, who is the expert from NOAA on this issue.

Senator GORE. Dr. Robert Wildman is the director of the Office of Oceanic Research Programs with NOAA. M. Grant Gross is director of the Division for Ocean Sciences at the National Science Foundation, and Courtney Riordan is director of the Office of Environmental Processes and Effects Research in the Office of Research Development at EPA. I want to welcome all of you, and Dr. Knauss, I am especially grateful to you for varying your schedule to come over here on a busy day. I really do appreciate it.

As I told you on the telephone, I believe the coral bleaching phenomenon worldwide represents the first biological signal confirming global warming. I believe that the temperatures for 1990, which now has been labeled as almost certainly the warmest year in recorded history by far, is significant and deserves a response from NOAA that is commensurate with the alarming nature of the evidence.

As I also told you, I want to ask you about our response to the broader phenomenon that this illustrates, namely, global warming. Since you are leading our team in that field now, we are very interested in what you have to say.

Before I have any questions, I want to invite you to make

## STATEMENT OF DR. JOHN KNAUSS, UNDER SECRETARY, OCEANS AND ATMOSPHERE, DEPARTMENT OF COMMERCE

Dr. KNAUSS. Well, Senator, I appreciate the opportunity of being here and I also appreciate the fact that you were able to make arrangements and changes in your schedule to meet mine.

I have a statement for the record, or rather a statement for the record that was actually in the name of Robert Wildman, who was going to give this testimony, and I would appreciate it if it could be entered into the record.

Senator GORE. Without objection, it will appear in full.

Dr. KNAUSS. As I am sure that you know by now from the experts who already appeared here that coral bleaching is a phenomenon which is natural, in the sense that it does occur on a more or less irregular basis over historic time. It is caused by the expulsion of the zooplankton, the zooxanthellae.

Zooxanthellae, apparently, as far as we understand it, is relatively temperature sensitive, it is also sensitive to other kinds of things, but a couple of degrees change in temperature up or down can essentially lead to the expulsion of the zooxanthellae, and with the result that the coral no longer are their darker color, but appear white. Coral bleaching is the term that is used.

Senator GORE. And are vulnerable to death if it is prolonged.

Dr. KNAUSS. If it is prolonged, that is right. They are, they can handle this sort of thing for a year, we are not quite sure how long they can handle it, but it is quite clear that, although it is a natural phenomenon, if it happens too often and too long, then these corals are under stress and, if they are under stress for too long, like the rest of us, they suffer damage.

This is not, this is clearly not the first time we have had coral bleaching. In the areas off, Bahama—areas, the historic record, as I understand it, goes back to about 1911, and we have seen it in years since then.

That is to be expected, I would think, because clearly the temperature, surface temperatures of the water do change from year to year, just as the temperatures of the earth change from year to year. There are variations of the order of a degree or two in year-to-year temperature changes in the atmosphere, and we have learned that there are, can be degree, degree changes, of a degree or more from year to year with respect to ocean temperatures, even in the tropics.

There is some evidence, evidence may be too strong a term, to suggest that these are somewhat related to the Southern Oscillation, the ENSO, that is, at least

when we have seen them, 1911, 1918, various years and so forth, it does seem to correlate with an El Nino-like phenomenon in the Pacific Ocean.

There is some limited theoretical evidence to suggest that there might be even reasons for this to be the case, but it is limited evidence at this point. Quite frankly, there has been limited study of this phenomenon. We at NOAA do not have a large program in this area, but I am told that we probably have the largest program in looking at these measures.

Senator GORE. Let me interject at this point, I do not want to interrupt your statement. Because of our effort to accommodate your schedule, you were not able to attend the entire hearing. I do want to alert you to the fact that we have had five experts in this field present a very lengthy——

Dr. KNAUSS. I will close my statement now, and I am ready for questions, sir.

Senator GORE. Let me ask one of those witnesses, Dr. Williams, if he will come back to the table here. The reason I do this, Dr. Knauss, is I want you to hear this. You have said that your understanding of this phenomenon is that it is related to El Niño events, but you offer the disclaimer that you are not an expert in this particular field and so forth.

Dr. KNAUSS. I said that there is some anecdotal evidence, almost, that the years that these have occurred in historic records do seem to be related to El Niño events. Whether there is a causal relationship, I am not prepared to say.

Senator GORE. I am not intentionally doing this, but I am keenly aware of the fact that you are at a disadvantage merely because of the circumstances. They result from your courtesy in coming to part of the hearing. But I want you to hear this.

Dr. Williams specifically addressed the El Niño question, and may I ask you a follow-up question, Dr. Williams. What has your team of scientists found about the appearance of bleaching phenomena not correlated with El Niño events?

Dr. WILLIAMS. Well, the—many of the early bleaching events were more localized, say, in the Florida Keys, did occur at the same time as El Niño events. But the recent events here in the 1980's seem to be much more large-scale and widespread and more serious than these early events.

And there have been four recent events in the 1980's that we recognize. Two of those did coincide with El Niño events—this serious bleaching in 1983 and 1987. However, there was just a beginning of an El Niño event in 1990 that never developed into a full-blown El Niño event.

Also in 1980, when we recognized a worldwide coral reef bleaching event, there was also the beginning of an El Niño event in the Pacific, but it never developed into what would be considered an El Niño at that time.

Senator GORE. Moreover, we got precise evidence, Dr. Knauss, which correlates the appearance of bleaching phenomena at widely varying locations with temperature peaks. We have heard from the scientists compiling the global temperature record from satellites that the global increase in temperatures in given years corresponds precisely with the occurrence of global mass bleaching events. So I would encourage NOAA to revisit this question.

Do you agree that NOAA should have more extensive efforts to look at ocean temperatures and the threat to corals?

Dr. KNAUSS. We certainly have increased our efforts at looking at ocean temperatures and particularly the year-to-year changes in ocean temperatures. We have increased that effort in the last few years, and I guarantee you we are going to increase that effort in the future.

Senator GORE. Very good. We also heard, Dr. Knauss, about the trend showing increased global temperatures over the last century, and the Huntsville team, whose work was misinterpreted earlier this year, came to clarify exactly

what their work means. They told us that their measurements correlate with the measurements of Phil Jones and others, which show a long-term warming trend.

Do you agree there is a long-term warming trend?

Dr. KNAUSS. Certainly based upon the temperature records that have been analyzed by scientists in the U.K. and elsewhere, there is clearly, over the last century, a long-term warming trend. That is right.

Senator GORE. Now, the increasing extent and frequency of coral bleaching and the new appearance of widespread die-off of coral after repeated stress from these incidents seems to be a biological signal that the continued warming over the last century has now reached a threshold beyond which biological signals like the dying of coral reefs may become more frequent. Do you agree with that?

Dr. KNAUSS. It is my under—if my understanding is correct, which is that namely these zooxanthellae are sensitive to changes of 1 or 2 degrees Celsius, then, yes, it seems to me that this is a, essentially a nonlinear response to a relatively small change in ocean temperature.

Senator GORE. To translate, nonlinear response suggests we are crossing a threshold beyond which things look different than they did before.

Dr. KNAUSS. That is right. I mean, just as you can, for example, if you change the water, the rainfall and so forth, you can suddenly change the ecology. You may change the rainfall just a small amount, but suddenly it becomes not possible for certain trees or certain plants to live, and then you have a whole new ecosystem move in.

I am not prepared to say we are heading in that direction yet with respect to corals. I do not think we know enough. But certainly the evidence of the last few years is disturbing.

Senator GORE. Now, you head the U.S. delegation to the Second World Climate Conference, which is the place where we are deciding how to respond to all this, correct?

Dr. KNAUSS. The Second World Climate Conference, Senator, is essentially divided up into two parts. There is a scientific discussion of the, of the issues of climate, and then there is a ministerial conference, which comes for 2 days at the end of that.

I am heading up the delegation, U.S. delegation to the ministerial conference. Joe Fry, from my office, who is head of our National Weather Service, is heading up the U.S. delegation to the so-called technical parts of the operation, of that conference.

Senator GORE. The preparatory sessions are underway now, is that correct?

Dr. KNAUSS. I do not believe so, I——

Senator GORE. I mean they just concluded.

Dr. KNAUSS. That is right. There was a preparatory session having to do with the ministerial part of this conference which just concluded in Nairobi, that is correct.

Senator GORE. Originally the scientific meeting at the Second World Climate Conference was intended to prepare a two-page summary of scientific conclusions to be passed on to the ministerial meeting.

Now, the United States delegation is trying to unlink the two meetings, namely, to keep the results of the scientific meeting out of the ministerial meeting, which you are heading. Is that correct?

Dr. KNAUSS. I would not put it in that way, no.

Senator GORE. Is the substance of it correct?

Dr. KNAUSS. I do not think so, sir. There is, indeed, going to be a statement of the scientific aspects of the Second World Climate Conference, and it is my view that that conference statement should be sufficiently complete that it can

stand on its own. And by standing on its own, if that means decoupling it from the ministerial declaration, then that can be an interpretation.

I do not interpret it as that. I feel that the Second World Climate, that the scientific discussions of the Second World Climate Conference are so important that it is critical that that part of the conference reach a conclusion—however many pages it is—which the conference, that part of the conference themselves can agree to.

Senator GORE. Now, we have proposed that—what would you say it should be called, instead of decoupling?

Dr. KNAUSS. I think it has to be able to stand on its own.

Senator GORE. The scientific——

Dr. KNAUSS. The scientific, that is right.

Senator GORE. But should it not be a part of the ministerial meeting?

Dr. KNAUSS. It certainly should be presented to the ministerial meeting. I am not sure how that ministerial meeting is going to come out at this particular point.

Senator GORE. Now, wasn't the scientific meeting originally tasked to prepare a two-page summary of the scientific conclusions to be given to the ministerial meeting?

Dr. KNAUSS. Senator, that may indeed be the case, but I am not aware of that. I would have to get back to you on that.

Senator GORE. Now, the United States, with a couple of other countries, including Saudi Arabia, has prepared 160 amendments to what was intended to be a two-page ministerial statement, resulting in a 30-page draft that seems to create tremendous difficulty for the success of the ministerial meeting.

Dr. KNAUSS. I have, since I have just been recently informed that I am going to be heading the U.S. delegation to that ministerial meeting, I have taken the trouble of looking at that draft and I concur with you.

Senator GORE. We are the ones that orchestrated that. Why did we do that?

Dr. KNAUSS. The ministerial draft that we saw was not very satisfactory.

Senator GORE. Was it too strong in stating that global warming was a problem?

Dr. KNAUSS. I think it was too strong in stating—let me back off, Senator. As you well know, we are heading for a world climate treaty, and those negotiations get underway in February in this country. It is our view that a number of things that were in the ministerial declaration should be subject to negotiations of the treaty and do not play a part in any ministerial declaration.

Given the fact that the minis—that the dele—that the treaty negotiations are going to begin in February, we believe that the ministerial declaration of the Second World Climate Conference should not get into the questions or the details of time limits for CO2 or greenhouse gas stabilization or reductions, but be more general. Timetables——

Senator GORE. More general?

Dr. KNAUSS. Timetables should be subject to treaty negotiation, not to declarations.

Senator GORE. Well, this meeting has been 2 years in the making, and now, at the last minute, the United States comes in with what appears to be a calculated effort to sabotage the meeting.

We were waiting for the IPCC for a long time, that was the excuse for not agreeing to do anything, and now the IPCC, the Intergovernmental Panel on Climate Change, has reported its conclusions. What are we waiting for now?

Dr. KNAUSS. We are not waiting, sir. That is why we are having the negotiations for the global change treaty beginning in February. The IPCC finished its deliberations its fall, and negotiations are beginning in February.

Senator GORE. But within the negotiations, we are taking the position, as you have just said, that we should not be agreeing to any reductions or goals or targets, but rather we should be more general in our conclusions. What are we waiting for before we agree to do something specific?

Dr. KNAUSS. We are waiting for the negotiations of that particular world climate treaty, for the negotiations. We are not going to use a ministerial declaration for making those decisions, or announcing those decisions.

Senator GORE. It seems to me that Mr. Sununu is handling the climate negotiations the same way he handled the budget negotiations. I happen to have a copy of some documents. We just came into possession of these.

Dr. KNAUSS. Which documents are you referring to, sir?

Senator GORE. How would you describe these? These are drafts of the ministerial statement which was proposed with the suggested U.S. changes that the Sununu team has recommended. I will get these copied. Let me read first, then I will give it to you. I do not want you to be without this.

One title is labeled Policy Targets for Urgent Action. We have recommended to change that to Policy Considerations. Paragraph 19 of the ministerial document says, "We agree that the ultimate global objective should be to stabilize and reduce greenhouse gas concentrations." The United States has proposed deleting that section.

The ministerial document said, in Article 20, "We stress, as a first step, the need to stabilize, while ensuring development of the world economy, emissions of greenhouse gases not controlled by the Montreal protocol." The U.S. has suggested, as an alternative—I will not read this long thing, but it says, "We recognize that the most effective response strategies, especially in the short term, are those which are economically efficient and cost-effective, able to serve multiple social, economic, and environmental purposes, justified for reasons other than climate change, administratively practical and effective," et cetera, et cetera.

Article 21 says, "We agree that stabilization of CO2 emissions should be achieved jointly by industrialized countries by the year 2000 and set at the lowest possible emission levels." The U.S. has proposed instead to recommend that limitation and adaption strategies be considered as an integrated package that complement each other to minimize net costs.

I am getting you copies of these right now. The pattern is real clear. We are proposing to weaken and dilute every reference in the ministerial document to proposals to actually do something about this problem. Is that the way you see it?

Dr. KNAUSS. I would think that the declaration, ministerial declaration, should build upon the concerns of the IPCC report which you have seen, should build upon the concerns that will be discussed by the scientists at the first part of the Second World Climate Conference, but should not get into detailed recommendations such as limiting CO2 emissions by the year 2000 or the year 2005 or 1995 or what have you.

Those are the kinds of things which I believe, and our Government believes, are subject to negotiations in a treaty, not first discussions, or declarations if you will, of a statement such as the kind that will come out of the ministerial declaration of the Second World Climate Conference.

Senator GORE. The official spearheading the U.S. effort appears to be a Mr. J.R. Spradley. Is he? Do you know Mr. Spradley?

Dr. KNAUSS. He works for me, sir.

Senator GORE. Who is he?

Dr. KNAUSS. He is a lawyer who is part of my general counsel and who is an expert in a variety of environmental issues.

Senator GORE. Why is he playing the lead role instead of the Environmental Protection Agency or the State Department?

Dr. KNAUSS. He is not playing the lead role. The lead role was played by the State Department. Mr. Spradley was only a part of the delegation, sir.

Senator GORE. Well, were you there?

Dr. KNAUSS. I was not there.

Senator GORE. Well, the people who were there said that Mr. Spradley played the lead role.

Dr. KNAUSS. The delegation, I believe, if you looked at the delegation list, I think you would not find that Mr. Spradley was chief of the delegation, sir.

Senator GORE. But he was the one who talked.

Dr. KNAUSS. I know several members of that delegation. I cannot believe that that is a correct characterization. I think they probably all talked.

Senator GORE. Well, the people who were there have given me detailed reports, and they all correspond with the observation that Mr. Spradley was in effect, the vocal leader of the delegation. So, I was just wondering. Is Mr. Reilly a part of our delegation to the World Climate Conference?

Dr. KNAUSS. As far as I know, he is not going.

Senator GORE. Why is that?

Dr. KNAUSS. Well, I did not make the decision that I was going to go. We have been taking turns, quite frankly. Bill Reilly goes to some, Mike DeLand goes to some, and I go to some. I went to Bergen, I am going to this one. Bill Reilly went to Nordwick, Mike DeLand headed up the U.S. team for the presidents.

Senator GORE. Mr. Spradley, according to the reports that I have received, caused an uproar during the discussions of oceans when he told Bangladesh not to worry about the impending sea level rise. The precise quote was, "Before you had cows, now you will have fish."

Had you heard that quote?

Dr. KNAUSS. No, sir.

Senator GORE. A lot of people were surprised by that statement.

Dr. KNAUSS. I am, too.

Senator GORE. If the scientific panel is decoupled from the ministerial meeting, might it become easier for the United States to dilute the expressions of urgency? Is our objective is to make the document more general and less specific, and to make the document less aimed at action and more aimed at rhetoric? That will probably be easier for us to accomplish if the scientific evidence about the seriousness of the problem is decoupled from the ministerial meeting. Would you agree?

Dr. KNAUSS. Well, that is not the interpretation I put on it. I have thought that there probably is not going to be much additional evidence other than what we have had from your first IPCC world climate assessment. And that is what we are all going to be living with for the next few years until there is a second assessment.

Senator GORE. This came out yesterday, or became available yesterday. The formal printed version of the IPCC's scientific assessment of climate change? It is entitled "The Policymakers' Summary of the Report of Working Group 1 to the Intergovernmental Panel on Climate Change." Have you had a chance to see this yet?

Dr. KNAUSS. I have not seen it in that form, no.

Senator GORE. Let me read one sentence from it. "Continuation of present-day emissions are committing us to increased future concentrations, and the longer emissions continue to increase, the greater would reductions have to be to stabilize at a given level. If there are critical concentration levels that should not be exceeded, then the earlier emission reductions are made, the more effective they are." Do you agree with that?

Dr. KNAUSS. Yes.

Senator GORE. Well, why is this being decoupled from the ministerial meeting?

Dr. KNAUSS. This is, excuse me, this is not being decoupled from the ministerial meeting. What is being decoupled, if anything is being decoupled, is there will be a statement——

Senator GORE. Right.

Dr. KNAUSS. Not of the IPCC, but there will be a statement of the technical sessions of the Second World Climate Conference.

Senator GORE. The scientific panel's assessment of the evidence and the timetable for this was geared to the completion of the IPCC process. Right?

Dr. KNAUSS. Yes, but it also had some other factors involved, one of which is is that, hopefully, this conference will deal with the agenda of action that must be taken by the scientific community in the future, and it is important that we reach international agreement on what that agenda should be. And that should not be confused with a political, a document that might be considered by some too highly political, which will be the ministerial document.

So I think they will be together, but my concern has been just the reverse of yours, Senator. My concern has been that I did not want to lose the momentum with respect to scientific concerns, monitoring of these kinds of things which are going to be discussed at the first part——

Senator GORE. Yeah.

Dr. KNAUSS. ——of the IPCC, and I wanted to be sure that that stood alone and could be agreed to and carried forward.

Senator GORE. Well, now, let us put this in the broader context. When George Bush was a candidate for President, he said that we will confront the greenhouse effect with the White House effect. He said that he was going to be the environmental President. He said that he was going to do something to deal with this problem.

Then, after the election, he started waffling. A phenomenon that is not uncommon, apparently, in this White House. And he began to say, we do not want to act until the IPCC has been completed. That was the excuse. When the IPCC process been completed, then we will act.

Now it has been completed, and still his team, which you have the discomfort to be heading has not acted. I think I know enough about you to believe that your personal views are probably different from the ones that you have to pursue in policy on this. You do not need to comment; you just need to look uncomfortable.

Which is probably not hard right now.

Dr. KNAUSS. I am not uncomfortable with the present U.S. Government position, sir.

Senator GORE. Well, the point is, after the IPCC process reached its conclusion, the world community began to prepare for this big meeting in February, where action is supposed to start. But the United States is now attempting to sabotage that meeting by insisting upon changes to every single part of the document that points toward action and by insisting that the scientific process summary be decoupled from the meetings where action is planned.

I think that the Bush White House is creating the same kind of catastrophe for the climate negotiations that it has engineered in the budget negotiations, and I do not think it is an accident that in both cases President Bush placed John Sununu effectively in charge of policy in both areas. This meeting, in February, that is the later meeting. This meeting due to take place in early November, what are the exact dates?

Dr. KNAUSS. November 6 and 7 is the ministerial, and I think the so-called technical meetings are the week previous to that. So it is the first week in November, more or less.

Senator GORE. Well, President Bush does not want a tax increase on the wealthy, and he does not want a reduction in CO2 emissions. We are insisting upon those objectives to the detriment of any agreement first. I do not want to mix these up too much. I am trying to make a point about the process, which I hope is clear.

In the case of climate change, we are seeing the same pigheaded, obstinate obstructionism from the Bush White House that we have seen in other negotiations. And I am extremely troubled by it.

Dr. KNAUSS. Senator, I probably am not going to be able to change your mind, but let me give you an alternative explanation of what is going on.

Senator GORE. All right.

Dr. KNAUSS. The IPCC finished its report in September, that was agreed to and sensible. There are two meetings that are taking place in the next few months after that. The first is the Second World Climate Conference, the second is the start of the negotiations for a treaty.

I would like to make the following kinds of distinctions, that it seems to be the Second World Climate Conference agenda should be to consider the future science agenda that must be considered to get on, so we better, so the second assessment of the IPCC in 3 years to 5 years will be better so we will know more.

The policy part of the issue raised by the IPCC should be taken up in the treaty negotiations. And those are two separate functions and they should not be confused.

Senator GORE. Well, now that is precisely what I mean by decoupling. That is what the U.S. is trying to do. That is not what most of the rest of the world wants to do. The real reason the United States is taking that approach is to torpedo the movement toward action, to actually do something in response to global warming. That is the not so well hidden agenda of the White House.

It is a charade by the White House, and I separate you from this, Dr. Knauss. You are an honorable man. You are a distinguished scientist, and I am pleased that you are involved in this process because here and there, where you have a chance to make a difference, I am confident that you will. But there is a larger agenda at work on the part of the White House here, and I think it is disgraceful myself.

We are, of course, increasingly alone in our refusal to act. The EEC and the European Free Trade Association nations, Switzerland, Norway, Austria, Iceland—are now working to stabilize greenhouse gases at current levels. Canada, New Zealand, and even Japan have announced similar goals.

And the idea that we should now be concentrating exclusively on improving the science is, in my view, unacceptable. I agree we ought to improve the science. But the time to act is now, and that is what the IPCC said. The President had said he was waiting for that it has come and gone, the President is still waiting.

I would like to ask, Dr. Knauss, if you could for the record, after you and your staff have had a chance to absorb the testimony of the coral bleaching panel and the testimony of the temperature panel, I would like to request that you supply

for the record your recommendations for adjusting the climate change program here in the United States to put a little more emphasis on the research agenda and the recommendations that we heard here today.

I believe they are extremely significant, and they come in both areas, incidentally. With respect to coral reefs, we had some very specific recommendations, and I would like your response formally to each one of them and your recommendations to the committee about how we can improve our research in that area.

Secondly, with respect to the collection of temperature data, both at ground level, which is very important on a continuing basis, and also from the new satellite measurement made possible by the work of the team in Huntsville, they felt that the research community in the global change program is not adequately informed about what they can do with these satellite temperatures now, and how to exploit that record.

Again, I realize you have not had a full chance to absorb what was presented to us here today.

Dr. KNAUSS. No, but I did read the science article on the Hunts—on the temperature records. I do keep up with a little bit of the material even without having to come to congressional hearings.

Senator GORE. Their appearance here today was partly to counter the misimpression given by the way the science article was hyped and ballyhooed in the press releases the magazine put out in advance. They distorted the meaning of the science itself, and the headlines further contracted the essence of that story.

Dr. Knauss, if you need to get back to your meetings, you are welcome to do so. We are going to take brief summaries from the other witnesses on this panel, then we will have questions for the record, perhaps a few short ones right here.

Dr. KNAUSS. Thank you very much, sir.

Senator GORE. Thank you very much, Dr. Knauss.

I would like to start with Robert Wildman, Director of the Office of Oceanic Research Programs at NOAA. If you could

## STATEMENT OF ROBERT WILDMAN, DIRECTOR, OFFICE OF OCEANIC RESEARCH PROGRAMS, NATIONAL OCEANS AND ATMOSPHERIC ADMINISTRATION, DEPARTMENT OF COMMERCE

Mr. WILDMAN. Senator, I think you have my testimony. Dr. Knauss has discussed some specific items there. In the interest of saving time, I simply will let the testimony stand and be willing to try to answer any questions you may have.

The statement follows:]

STATEMENT OF ROBERT WILDMAN, DIRECTOR, OCEANIC RESEARCH PROGRAMS, NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, DEPARTMENT OF COMMERCE

Mr. Chairman and Members of the Committee: My name is Robert Wildman. I am Director of the Oceanic Research Programs for the National Oceanic and Atmospheric Administration (NOAA) U.S. Department of Commerce. I appreciate the opportunity to discuss the bleaching of tropical Atlantic coral reefs in the Caribbean and the Atlantic waters.

In August and early September 1990 NOAA personnel as well as others in the Florida Keys and Bahamas, observed a new outbreak of coral bleaching. As experts and others know, this is not the first incidence of coral bleaching nor is it likely the last to be seen in these areas. A coral bleaching outbreak in 1987 raised considerable concern in the marine community and led to hearings held by the Senate Appropriations Committee, chaired by Senators Hollings and Weicker. One of the findings of this hearing was the lack of knowledge into the cause of coral bleaching events. After that hearing NOAA took several steps to improve the data base on coral bleaching and is continuing this endeavor.

Following a brief review of corals and possible causes of coral bleaching, I will review what NOAA has done and is planning to do about coral bleaching.

Coral reefs are highly complex tropical ecosystems rivaled only by tropical rain forests in their diversity. Coral reefs are major components of shallow-water marine ecosystems in the tropics. They support commercially important fisheries and have substantial tourism value.

Coral bleaching is the mass expulsion of zooxanthellae from the coral tissue. Zooxanthellae are symbiotic algae that live within the tissue of corals, which help corals grow and provide a major source of energy to the host coral animal. The reef building nature of corals is due to this symbiotic relationship that improves growth rates. Corals can live without the zooxanthellae but do not grow well and are more susceptible to stress related mortality. Zooxanthellae give the coral a brownish tint, thus when expelled leaves the coral with a colorless tissue overlying a white stone-like carbonate matrix giving the appearance of bleaching. Zooxanthellae expulsion is a natural event by which corals dispose of older, morbid, or dead cells. During bleaching not all the zooxanthellae are necessarily lost, thus coral can survive bleaching by redeveloping the algal colony. The actual mechanism of expulsion is still not well known. Not only stony corals, the major reef builders, are affected but also other cnidarians such as soft corals (gorgonians) anemones, and hydrozoans (fire coral). Expulsion of the zooxanthellae is a continuing natural process, but mass expulsion leading to coral bleaching is caused by physiological stress. In the laboratory such factors as high or low temperature, high or low salinities and high or low irradiance are known to cause bleaching. As little as 1 or 20C difference in water temperature outside the optimum range of 27-30C can cause bleaching. In nature there appears to be a correlation between the incidence of bleaching and elevated water temperature.

Bleaching has both short-term and long-tern ecological effects. Short-term effects include increased vulnerability of corals to other sources of stress, increased coral mortality, reduced coral growth, and increased bioerosion. Long-term effects include loss of reef framework leading to loss of habitat and shoreline protection and ultimately to declines in fisheries and tourism value.

Because corals are sensitive to small changes in water temperature (possibly as little as 1C) they may be good indicators of climatic change assuming water temperature change is linked to climate change. An advantage to using corals as a monitor of climate change is their responsive on short time scales to environmental factors.

Although direct anthropogenic effects such as eutrophication or sedimentation may cause bleaching, the widespread nature of the present and 1987 events, especially in areas with limited human impact (e.g., Bahamas), suggest a possible overall decline of this tropical ecosystem.

In contrast to Pacific coral reef s, Caribbean reefs are frequently dominated by long-lived species suggesting that they are not normally subjected to frequent catastrophic mortality. Caribbean coral life history strategies, such as limited dispersal and slow growth, indicate that rapid recovery from catastrophic mortality is unlikely.

Determining whether the cause of this bleaching is a natural or anthropogenic driven process may be extremely difficult. For example, some years ago the outbreak of the crown-of-thorns starfish on Pacific reefs was initially attributed to anthropogenic causes, but more recent analyses indicate a natural cycle for the outbreak.

In order to determine the cause of coral bleaching a logical and efficient research program is necessary, which should study historical events, determine natural cycles, and better understand the basic biology of corals. This is presently underway in the marine community.

Naturally occurring bleaching events can be caused by unusual short-term climatic events, such as extreme low tide during mid-day. Bleaching events of sufficient magnitude to attract notice occurred in 1911, 1918, 1958, 1973, 1983, and 1987 in the Florida Keys.

The 1987 bleaching event affected parts of the Gulf of Mexico and the Caribbean including reefs from Texas and the Bahamas to Panama and Colombia. Based on the limited historical record, the 1987 event was the most massive known in Florida in geographic extent (Palm Beach to Dry Tortugas), bathymetric extent (surface to 25 m) and longevity (July to December). Although the bleaching was extensive, no major coral mortality was reported in Florida.

Elevated water temperature was indicated as the most likely cause of the 1987 coral bleaching. Water temperatures in Florida were 2-3C above normal. Elevated temperatures were coupled with calm weather in many areas, which may have intensified the effect, if it was not the root cause.

A large-scale climatological process is needed to explain a Caribbean-wide phenomenon, such as the 1987 bleaching event. Major coral bleaching and mortality on Eastern Pacific reefs followed the strong 1982-83 El Nino-Southern Oscillation (ENSO) event. Interestingly the 1987 Caribbean event was also preceded by an ENSO event. Looking back through time, known Florida Keys bleaching events in 1918, 1958, 1973, and 1983 were preceded by ENSO episodes. ENSO events in 1925-26, 1932, 1940-41 had no reported bleaching associated with them, though reef monitoring was poor during that time.

The widespread nature, rapid start, and depth range of the 1987 event seems to rule out causes other than water temperature (such as, water-borne pathogens and excessive irradiation).

Previous NOAA activities relevant to coral reef investigations include in-situ research on factors affecting growth and mortality in corals using NOAA's National Undersea Research Program (NURP) undersea habitat facility (AQUARIUS) at St. Croix. In the fall of 1987, NURP through its Caribbean Marine Research Center (CMRC) began the installation of a regional network of recording

thermographs at various depths throughout the Caribbean with the assistance of members of the Association of Is land Marine Laboratories of the Caribbean (AIMLC). Presently NURP has in place a network of 22 thermographs in the Caribbean in water depth from 2 to 160 m. Preliminary analysis by CMRC is underway on temperature records at selected stations. This analysis, detailed in testimony by Mr. Robert Wicklund, Director of CMRC, shows that 1990 is another warm water year when compared to 1988 and 1989. Both high and low temperatures at two and 20 m in August and September 1990 were about 1.5C higher than in 1988 and 1.0C higher than 1989 in the Bahamas.

In addition NURP is developing undersea tools to core corals and tap the paleoclimatic record retained in their growth bands.

In the Florida Keys, NOAA' s Sanctuary Program personnel have been monitoring coral reef health for the past ten years. Also, the Sanctuary Program has established a network of 24 thermographs from Biscayne to Key West to monitor water temperature in the Florida Keys, and this summer began monitoring water temperature at the Flower Garden reefs in the Gulf of Mexico.

In 1988, following the 1987 bleaching event, NURP sponsored a workshop on mass bleaching in the Caribbean to develop a region-wide research strategy. Sampling protocol was instituted and an observational network established through AIMLC. NOAA' s Sanctuary Program, following recommendations of the 1988 workshop, established periodic photographic transects to permit quantitative measurement of coral reef changes on a species by species basis in the Key Largo and Looe Key National Marine Sanctuaries.

Based on the recommendation of the NURP workshop, NSF under their rapid response program funded field monitoring in Florida, Bahamas, Puerto Rico, St. Croix, and Venezuela directed by Dr. Judy Lang, of the University of Texas. In addition, CMRC has expanded its network of recording thermographs in the Caribbean.

Concern for the general deterioration of marine habitats in the Florida Keys resulted in a NURP sponsored workshop in 1988 to develop research and management strategies for the Florida Keys reef tract. As a result of this workshop, the MacArthur Foundation has provided funds for a multi-year monitoring program in the Florida Keys directed by Dr. John Ogden at the Florida Institute of Oceanography.

NOAA's Sanctuary Program now has several years worth of reef transect data to review changes due to recent events. The program will also monitor water temperature throughout the Florida Keys and at the Flower Gardens off Texas.

The coral bleaching now occurring at several sites in the Caribbean, is not of the magnitude and extent of the 1987 event. However there appears to be more mortality so far this year than in 1987. NOAA's Sanctuary Program reports the bleaching in the Florida Keys, which started in late August and early September 1990, is producing extensive mortality in fire and elkhorn corals. Mortality in fire coral is also reported at the Flower Gardens. Coral bleaching was also first observed this year in the Bahamas in August by NURP CMRC scientists.

For the future NOAA will continue its current activities as follows:

The Sanctuary Program plans to further develop coral reef monitoring in the Florida Keys, especially in light of the proposed expansion of the marine sanctuary to encompass the whole area of the Keys. Also the designated sanctuary site at the Flower Garden Banks will be monitored.

Coral reef ecosystems research will continue as part of our Marine Ecosystems Response Project within the Global Change Research Program. This program may assist in developing a research plan to study coral bleaching.

Mr. Chairman, that concludes my prepared statement. I will be happy to answer any questions the Members of the Committee may have.

Senator GORE. Very good. Thank you.

M. Grant Gross, Director of the Division of Ocean Sciences at NSF.

## STATEMENT OF M. GRANT GROSS, DIRECTOR, DIVISION OF OCEAN SCIENCES, NATIONAL SCIENCE FOUNDATION; ACCOMPANIED BY DR. PHIL TAYLOR

Mr. GROSS. Thank you, Mr. Chairman. I am glad to be here. I am accompanied today by Dr. Phil Taylor, who is an expert on coral bleaching. If you have any specific questions, he is here to answer them.

Let me highlight the testimony which you have in front of you to point out first that NSF basically responds to proposals primarily from individuals or small groups of individuals to do research. The bottom line of the research that we have supported to date in the area of coral reefs and coral bleaching is that there is still many, many questions about the exact processes involved and that these are still

areas of very active research by scientists and U.S. colleges and universities. Some of them supported by NSF, some supported by Sea Grant.

Let me give you an example of the type of projects supported. Professor Glynn of the University of Miami investigated the coral bleaching and coral deaths resulting from the 1982-83 El Niño and documented the processes. In addition, he showed that approximately 400 years of records of previous events can be analyzed from the recorded rings that the corals lay down. We have a record which goes back in time to augment the records which we have heard discussed both from the surface observations and from the more recent satellite observations.

We have also supported projects investigating the 1988 bleaching events. None of these have been completed. Let me simply summarize by saying we believe we have mechanisms in place that will lend themselves very well to the studies conducted in the U.S. universities and colleges. Our regular research projects are a little bit slow to respond to something that is happening on the order of days and weeks. We have another program called Small Grants for Exploratory Research, which permits up to $50,000 to be awarded within a matter of a month or so, so we can get an investigator into the field to look at something while it is still going on, to look at the processes involved. We believe that can be a very important part of the sort of national response to coral bleaching.

Two other programs, which to date have not been used in this area provide opportunities for longer-term research. One of these is long-term ecological research where we provide—and this has been in operation for about 10 years—support to follow events over long periods of time and the ecological responses to those events.

To my knowledge, we have not supported such long-term research on coral reefs, but there is certainly nothing that would prevent it. That may well be a part that would come into play in the future. In addition the more recent research program is the Land Margin Ecosystem Research, which again would lend itself to coral reef studies.

We believe that the Foundation can respond to U.S. scientists as they formulate research programs. It is a little surprising to me that we have not seen more proposals. I suspect with the kind of evidence which we have heard from the previous two panels, we may well see some proposals on our doorstep in the very near future.

[The statement follows:]

STATEMENT OF DR. M. GRANT GROSS, DIVISION OF OCEAN SCIENCES, NATIONAL SCIENCE FOUNDATION

Mr. Chairman and Members of the Committee: I am M. Grant Gross, Director of the Division of Ocean Sciences, National Science Foundation. I am pleased to be here today to discuss NSF-supported projects to determine the causes and significance of Coral Bleaching in the reefs of the western Tropical Atlantic Ocean, including the Caribbean Sea.

Let me begin with the bottom line. We do not know what is causing the present episode of coral bleaching - the expulsion of microscopic algae from the tissues of living coral animals. We do know that environmental stresses, such as extreme temperatures, low salinity, and reduced light intensity, will result in bleaching. What is causing the present bleaching episode is an active subject for research by scientists, some supported by the National Science Foundation.

The most commonly accepted explanation is that the increase in coral bleaching is caused by elevated sea water temperatures - perhaps 1 to 2C - which approach the upper temperature limits of the coral animals involved (or their algal symbionts). We know that many such animals in tropical oceans live near the extreme upper end of their temperature tolerance range. Thus a few days of unusually warm, calm weather may cause elevated water temperatures that stress animals living in shallow waters. Many scientists believe that the increased temperatures during the 1980s may be enough to trigger the observed coral bleaching, but we cannot yet prove this hypothesis.

Coral bleaching results from the expulsion of microscopic algae that normally live in the tissues of coral animals. This expulsion, in turn, causes the normally green or brown-colored coral animals

to become transparent so that the underlying white coral skeleton is visible - thus the term "bleaching". Most of the corals involved do not die and later recover. The algae are important to coral health and growth because they provide food and oxygen to the coral and assist it to lay down the hard carbonate skeletons that make up the mass of coral reefs. Episodes of coral bleaching have been reported in 1979-80, 1982-3, 1986-8, and again locally this year.

Professor Peter Glynn, at the University of Miami, investigated the effects of the 1982-83 El Niño on the coral reefs of the tropical Eastern Pacific Ocean. His results showed that prolonged elevated seawater temperatures could cause bleaching and even coral death if the high temperatures persisted. Professor Glynn and his coworker, Professor L. D'Croz of the University of Panama, showed that high temperatures alone can account for damage to coral reefs. Professor Glynn also showed that growth bands in 400-year old corals living in the eastern tropical Pacific recorded several events similar to the 1982-83 El Nino. The temperature conditions associated with El Ninos are the result of natural oceanic processes and are not a manifestation of global warming.

NSF has supported a number of research projects to study various aspects of the processes of coral bleaching observed in the 1988 bleaching event. Professor Leonard Muscatine, of the University of California at Los Angeles, is currently examining how environmental stresses, including temperature, can cause expulsion of algae from reef- building corals and other tropical organisms. This study is intended to provide information about the basic mechanisms involved and to help scientists interpret observations of future bleaching events.

Professor James W. Porter and coworkers at the University of Georgia monitored bleaching events at the Key Largo National Marine Sanctuary in 1988. They have also been following the subsegment recovery of the corals. Their work is not yet complete.

Professor Judith Lang, of the University of Texas, also received rapid response funding to study coral bleaching in the western tropical Atlantic Ocean in the 1988 event. She has been studying reefs in Venezuela, St. Croix USVI, Florida Keys and the Bahamas in great detail.

Future NSF-supported research on coral bleaching is likely to involve studies by individual scientists of both the basic mechanisms involved and the associated environmental conditions. Our program of "Small Grants for Exploratory Research" is an especially effective mechanism for rapid funding of studies of ocean processes affected by environmental events. Such a mechanism permits a rapid response to the study of bleaching events by providing funds (up to $50,000) to permit scientists to quickly investigate events while these events are still in progress. Thus NSF will be able to respond rapidly to support requests to investigate bleaching episodes.

In summary, we at NSF believe that continued support of basic research studies by US ocean scientists and biologists will eventually unravel the mystery of coral bleaching. The process of funding research at American universities also educates new generations of scientists to deal with these and future problems as our planet continues to adjust to the changes caused by human activities and to the natural variability of the climate system.

I will close by mentioning the work that NSF and other federal agencies are supporting to investigate the larger questions of Global Climate Change. US scientists at universities and Federal laboratories are combining forces with their colleagues around the world to investigate the larger questions of how Earth and its organisms are responding to environmental changes caused by human activities. These studies include investigations of the social dimensions of global climate change causes and of means to lessen the effects and to cope with those changes that we cannot influence.

Senator GORE. Very good. Our final witness is Courtney Riordan with EPA.

## STATEMENT OF COURTNEY RIORDAN, DIRECTOR, OFFICE OF ENVIRONMENTAL PROCESSES AND EFFECTS RESEARCH, OFFICE OF RESEARCH AND DEVELOPMENT, ENVIRONMENTAL PROTECTION AGENCY

Mr. RIORDAN. Thank you, Senator. Like the others, if I may, I would like to submit my formal testimony for the record.

We in the research and development programs at EPA are not currently carrying out in-house or funding extramurally any research in the area of coral reef bleaching. Our recent review of the evidence, however, conducted primarily in response to this hearing, has convinced us that the issue is important and of legitimate environmental concern.

We think the issue is relevant to at least two major problems that we face today, climate change and the loss of biodiversity. For this reason, we believe that further assessment of the issue in more depth, with more expertise than we have, and over a longer period of time should be carried out to determine what

priorities should be placed on additional research and monitoring to deal with this issue.

We had suggested, prior to your request to Dr. Knauss, that we would recommend this approach to the task group on ecodynamics and effects—ecological systems and dynamics and effects subgroup of the CEES as a priority issue for review. Reviewing the state of knowledge relative to what is going on in the current Federal research program to see how we might make more explicit what is currently going on in the Federal research program and how that would contribute to elucidating the temperature record, both surface sea temperature record and atmospheric temperature record, as well as the satellite programs that are planned and how they would contribute to monitoring the coral reef question.

But in addition it seems that priority should be given to examining what additional research proposals might contribute to further elucidation of the issue. Along the lines of the request that you made to Dr. Knauss, I think as a result of this meeting we would simply suggest that Dr. Knauss, and I am sure he will, would coordinate his response to your committee by way of the CEES task groups.

Thank you, Senator.

[The statement follows:]

STATEMENT OF DR COURTNEY RIORDAN, DIRECTOR, OFFICE OF ENVIRONMENTAL PROCESSES AND EFFECTS RESEARCH, OFFICE OF RESEARCH AND DEVELOPMENT, ENVIRONMENTAL PROTECTION AGENCY

I am pleased to be here today to discuss the bleaching of coral reefs. While we are not currently working in this specific area, our recent review of the evidence—conducted in response to this hearing—suggests that this is a matter of legitimate environmental concern. This issue may relate to two major problems, climate change and biodiversity, or habitat preservation. For this reason, further scientific assessment would appear to be in order to determine how high a priority should be placed on additional research on or monitoring of coral reefs.

It is common knowledge that tropical coral reefs—complex assemblages of plants and animals—are among the most diverse and productive habitats in the world. Reefs are structurally dominated by coral animals whose growth and survival is related to plants, unicellular algae called zooxanthellae, which live symbiotically inside the corals. The zooxanthellae are an important source of nutrients and oxygen for the corals. Numerous species of fish, invertebrates, and plants also depend upon and form coral reef communities. The presence of coral reefs also protects the coastal Coral respond to a range of stress by losing their zooxanthellae or ability of these symbionts to produce nutrients and oxygen. This phenomenon is termed bleaching. The stresses suggested to be related to bleaching include: salinity, temperature, darkness, ultraviolet radiation, or changes in nutrients. Some studies show that brief episodes of several degree centigrade elevations in temperature can lead to bleaching or that smaller, longer term elevations can also lead to such bleaching.

The consequences of the loss of the symbiont can include coral death, or sublethal effects on the corals such as growth loss or loss of reproductive capacity. In some cases where the damage has been sublethal, complete recovery of the coral including its symbiotic relationship has been reported.

Reductions in coral growth would lead to a reduction in the carbon sequestration capacity of tropical marine ecosystems and thus serve as another positive feedback to climate change. However, while the net primary productivity of coral reefs is among the highest of any ecosystem in the world, their limited areal extent may limit their role in controlling carbon fluxes globally. There are other compounding factors; any change in reefs would lead to changes in fish and other plants and animals dependent upon the reefs. Investigators have suggested that the bleaching reflects an array of stresses—the combination of which differs from place to place. Ultimately,. the answers to these questions are important.

The evidence assembled, particularly by Dr. Williams, shows that bleaching of coral is a widely reported phenomenon occurring on Pacific Ocean, Indian Ocean, Atlantic Ocean and Caribbean Sea reefs. The recently reported bleachings have been related to temperature increases. Many of the instances, ranging from Indonesia through the eastern Pacific and into the Caribbean have been attributed to temperature changes that result from El Nino. Some have asserted that these temperature increases are further related to patterns of global climate change.

In terms of concern about the sustainability of the resource base and the ecological functions which it provides, it would seem prudent to evaluate the short and long-term causes of bleaching because of the multiple roles which coral reefs play:

1. Coral reefs are an important part of the marine ecosystem, particularly its bioenergetics,
2. They are an important control mechanism protecting against coastal erosion,
3. Coral reefs are a potentially sensitive indicator of anthropogenic stress in tropical waters,
4. They are a potentially sensitive indicator of temperature variation which might mirror global climate change, and
5. Coral reefs may be a foundation for comprehensively evaluating the extent of ecosystem changes, particularly for evaluating the magnitude of positive or negative feedbacks to climate change.

We intend to recommend to the Committee on Earth and Environment Sciences (CEES) chaired by Dr. Dallas Peck that the Committee request its Task Group on Ecological Systems and Dynamics to undertake review of the existing data, studies and conclusions within the next few months. We will propose that CEES address not only the nature of the phenomenon, but also attempt to estimate the magnitude or the potential magnitude of the consequences. We will recommend the Joint involvement of other Federal and state agencies in this endeavor. Such an evaluation would be a foundation for making further decisions about the priority of future research in this area.

This completes my prepared testimony. I would be happy to answer any questions you have.

Senator GORE. Thank you very much.

Dr. Wildman, Dr. Hayes and the other members of the first panel involved in coral bleaching research have called once again for the establishment of a central reporting facility and alert network to enable them to monitor and assess the health of the oceans. It seems that a natural home for such a system may be in UNEP's regional seas program.

We are participants in both the Caribbean and South Pacific regional programs. What has been our involvement in these programs to date and what are the prospects for our increased participation in these projects in the future, specifically in setting up the reporting network that these scientists have been calling for?

Mr. WILDMAN. Senator, I would have to provide you with the details on past involvement with UNEP. And as far as a new system that we could support, that would be one of the things we would have to consider amongst our priorities. But we are looking at this whole area as a matter of concern relative to global change. That might be a logical place for that kind of activity.

Senator GORE. My information is that NOAA would like to increase its activities under this program, but the State Department is blocking it. We have contributed in the South Pacific, even though this is only due to AID contributions. We have been noncooperative in the Caribbean. Even though we have been signatories to the Caribbean Action Plan since 1981, we have only contributed money to projects in one year—in 1987. At other times we have given very small amounts for administrative costs but not to fund any projects.

Are you aware of that?

Mr. WILDMAN. No, I was not.

Senator GORE. Could you check into it and respond for the record.

Mr. WILDMAN. Certainly.

Senator GORE. My information is that NOAA is supportive, but the State Department is blocking it.

In the original budget proposals submitted by the President for fiscal year 1991, $87 million is requested to fund NOAA's involvement in the climate and global change program. According to documents accompanying the budget submission, part of that money is to fund studies of ocean atmosphere interactions and the response of marine resources to climate change and related stresses. Will studies of coral reef bleaching be funded as part of this initiative?

Mr. WILDMAN. They are one of the priority areas being considered. I think that will depend largely on the final funding available for the entire global change program.

Senator GORE. I take it from the testimony of this panel that you have listened to the coral bleaching experts here and others, and you believe we ought to

reassess the amount of attention we are paying to this and upgrade it. Is that a fair summary of what you all are saying? Mr. Gross?

Mr. GROSS. Well the response that we make, of course, depends on how the university community responds. If they recognize this as a high-priority area with opportunities for scientific advance we will very likely see proposals. And I suspect based on what we have heard they are very likely to be very competitive.

One other piece that I should point out in the way that the Foundation supports research at the universities, not only does it do research on the questions involved, but it also is a primary mechanism for training the new generation of researchers. We feel that looking at the processes involved in detail—really find out what is going on—and also making sure that we have the next generation of trained scientist ready to take on problems as they appear are very important parts of our mission.

Senator GORE. How much money did NSF spend last year on understanding coral reef ecology?

Mr. GROSS. The total amount is on the order of about $1.25 million, about $.5 million went into coral bleaching event studies, process studies primarily. And almost $.75 million into coral reefs in general.

Senator GORE. You stated that the commonly accepted explanation for the increase in coral bleaching is now elevated sea water temperatures. Then you state many scientists believe that while the increased temperatures in the 1980's may be enough to trigger the observed bleaching, we cannot yet prove this hypothesis.

What alternative hypothesis would you put forward?

Mr. GROSS. Well, I was thinking when I wrote that of some of the work that Dr. Williams has presented; there may be a variety of factors involved here.

Senator GORE. But after hearing him and seeing the evidence presented, would you want to modify that?

Mr. GROSS. I think that there is a much more compelling case for temperature as a prime factor at this point.

Senator GORE. All right. Mr. Riordan, you state that the EPA is not currently working in the specific area of coral bleaching. In the report accompanying the President's 1991 global change request, however, EPA requests $26 million to use, in part, to quantity and model the consequences of climate change on ecosystems. Moreover, the request states that special emphasis will be given to climate-sensitive regions.

It seems to me that coral reefs are just such systems. In what way do you expect EPA's activities with respect to coral reefs and with respect to the oceans as an integral part of our global climatic balance will intensify in 1991? I would like you to be specific as to the initiative you foresee and the ones you had in mind when you requested the $26 million.

Mr. RIORDAN. Our request was focused on the terrestrial environment and the effect of global change on its redistribution. In the planning programs and in coordination with other Federal agencies, we tended to defer to NASA, NOAA and NSF in the area of the marine environment. We had proposed only a very small effort in marine environment having to do with the ecological consequences of intervention in the marine environment.

For example, with regard to fertilization proposals that might be proposed, we were concerned about what the potential disruptive ecological effects would be associated with those kind of activities, and proposed to do some baseline work in that area.

In our draft effects report, we did identify bleaching of coral reefs as an issue, but we have not gone into it in much depth because in that instance we were

focusing heavily upon sensitive ecosystems in the continental United States. I think as a result of this hearing and as a result of the information that has been made available, as I said in my testimony, we should reassess the situation in cooperation with the other agencies to see what we might do in terms of focusing 1991 resources.

Senator GORE. That is excellent. Thank you very much.

Dr. Wildman, in your testimony you mentioned various initiatives that NOAA has undertaken to further the study of coral reefs. Most of the initiatives you mentioned are part of the NURP; that is, the National Undersea Research Program. In your budget submission for 1991, however, you ask for no funding for that program.

How do you propose to fill the void?

Mr. WILDMAN. Well, Senator, the decision to not request funding for NURP was one based upon a lot of competing demand for our total budget for the agency. I do not think that there is a suggestion there that NURP has not been a worthy program, but we simply could not obtain funds for all. It will be difficult to provide support for these same types of studies if there is not a continuing funding of the NURP program. Some part of it could be supported through the Sea Grant program, but some of the activities that NURP does support involve undersea vehicles of various kinds. We simply do not have that capacity.

Senator GORE. We have gone longer than I had anticipated today, but we have covered a lot of ground. I would like to thank all of our witnesses. I think it has been a very interesting hearing, and I appreciate all who have contributed to it.

With that, we will stand in adjournment. Thank you.

[Whereupon, at 12:55 p.m., the hearing was adjourned.]

[The following information was subsequently received for the record:]

STATEMENT OF JOHN C. OGDEN, PH. D., DIRECTOR, FLORIDA INSTITUTE OF OCEANOGRAPHY

1. THE HISTORY OF BLEACHING OBSERVATIONS

Coral bleaching was first noticed in the field as long ago as 1931, but the extensive bleaching of corals in the IndoPacific in 1983 and in the Caribbean in 1987 brought it into prominence. Bleaching has been observed extensively in the Florida Keys where it shows a remarkable correlation with the El Niño Southern Oscillation (ENSO), a global atmospheric disturbance causing periodic (3 to 10 years) disruption of the currents in the Pacific Ocean. Bleaching may occur regularly on coral reefs on an approximate 5 to 10 year time scale.

2. DEFINITION OF BLEACHING

The term bleaching refers to the loss of color in normal corals (and other related organisms inhabiting coral reefs) that can be attributed to: (1) a reduction in the number of plant cells (called "zooxanthellae") living in symbiotic association with coral tissue; (2) a reduction in the pigment (mostly chlorophyll) contained within the zooxanthellae; or (3) a combination of both.

3. THE CAUSES OF BLEACHING

While the causes of bleaching of corals are not presently known, it is widely believed and reported that corals bleach due to a physiological disruption of the symbiotic association between coral and zooxanthellae brought on by: (1) abnormally high seawater temperatures; (2) high seawater temperatures for abnormally long periods of time; (3) high levels of light irradiation in coral reef areas brought on by abnormally calm winds and glassy sea surface conditions; (4) some combination of these influences. There has also been the suggestion in many of the published reports that corals stressed by other factors such as disease, sedimentation, or pollution will have a greater tendency to bleach.

4. THE EFFECTS OF BLEACHING

Corals (and other reef dwelling organisms with zooxanthellae) bleach in a wide variety of patterns. If bleaching is severe, the effect is very startling to the eye, with large areas of reef turned pure white (a very rare color on the reef). For the most part, bleaching is not fatal to the affected organisms. Portions of a coral may die and be eroded or the coral tissue may grow back over the dead areas. However, some reports indicate that if bleaching is prolonged, affected organisms may die. So far there have been no studies identifying bleaching as a major cause of permanent damage to coral reefs

in the Caribbean. However, bleaching of the coral reefs of the tropical eastern Pacific associated with the 1982-83 El Niño (and prolonged exposure to high temperature) were heavily damaged by high incidence of coral mortality.

5. HOW GOOD IS THE EVIDENCE THAT HIGH SEAWATER TEMPERATURES CAUSE BLEACHING?

The correlation of bleaching with high seawater temperature and or prolonged periods of high temperature is consistent. In experimental situations corals have bleached when held at temperatures typical of field conditions which cause bleaching. There seems little reason to doubt that elevated seawater temperature is the proximal factor in the bleaching response.

6. IS CORAL BLEACHING AN EARLY WARNING OF WARMING OF THE OCEANS AND GLOBAL CLIMATE CHANGE?

In order for bleaching to be interpreted as a signal of the warming of the ocean, we have to acknowledge two critical difficulties.

a. We do not know if bleaching has been a regular event in the past, similar to, for example, hurricanes, the El Niño current of the Eastern Pacific, or the periodic outbreaks of the crown-of-thorns starfish (Acanthaster nlancii) in the tropical Pacific Ocean. Coral reefs have been under intensive scrutiny for only about 25 years. Natural cycles of atmospheric and biological disturbances commonly occur on longer time scales. Prior to 1965, coral bleaching would not have been widely noticed.

b. In contrast to atmospheric temperatures, where there is at least credible evidence for warming since the industrial revolution, there are no comparable records of seawater temperatures. For example, the Sea Surface Temperature (SST) satellite observations are made on too large a geographic scale to be useful and are often obscured by clouds. At the U.S. Senate hearings chaired by Senator Lowell P. Weicker Jr. in November 1987, following the first widespread notice of the bleaching phenomenon, the most startling fact revealed was the lack of long-term seawater temperature records for the Caribbean. The strongest recommendation of the hearings and the subsequent workshop of scientists was that a program of coordinated long-term observations of the tropical western north Atlantic be undertaken as soon as possible. This program would anticipate the need for data on global climate trends in the ocean and future management obligations. In spite of this recommendation, there is to date no broad scale coordinated program in the Caribbean to conduct such observations. Several proposals have been made but there has been little agency interest.

7. CONCLUSIONS AND RECOMMENDATIONS

a. Bleaching of corals and other reef-dwelling organisms bearing zooxanthellae has been associated with elevated seawater temperature, high temperatures for prolonged periods, or both of these factors.

b. We cannot say that bleaching is a result of global warming in the oceans as we generally lack long-term temperature records and we have only been looking at coral reefs for the past 25 years. Bleaching may be a manifestation of a periodic regional atmospheric- oceanic event which causes elevated temperatures in inshore areas where coral reefs thrive.

c. Bleaching must be understood within the context of coral reefs which are directly or indirectly suffering the stresses of over-exploitation world-wide. Thus, while bleaching of reef-dwelling may be an indicator of global warming in the ocean, the sensitivity of the indicator is strongly affected by non-temperature related stresses.

d. A program of systematic long-term observations (including seawater temperature) within defined zones of the tropical western north Atlantic (e.g. the Caribbean Sea, South Florida, Bermuda, etc.) is required. This program is the only way to document with assurance the response of the ocean to global climate change, take advantage of scientific opportunities that will arise, and to provide input to management. Such a program would be appropriately funded by a coalition of the many agencies which have global change research initiatives in response to the scientific and popular concern with global warming and sea level rise.

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